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A HIGH ENERGY DENSITY STORAGE SYSTEM WITH ENCAPSULATED SILVER-ZINC CELLS FOR DEEP OCEAN APPLICATIONS

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This investigation is concerned with the design of a high energy density storage system for deep ocean applications. A sampling of available storage cells is presented and their properties compared with those of the silver-zinc cell. The concept of packaging large numbers of silver-zinc batteries in small glass spheres is then developed, and systems capable of positive, neutral, or negative buoyancy are shown.

These individual battery packages are integrated into complete electrical systems and the manner in which they are to be carried by a DSV is shown. Finally, the advantages of the pressure-proof silver-zinc system are demonstrated by means of a comparison with the popular pressure-compensated system.

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A HIGH ENERGY DENSITY STORAGE SYSTEM WITH ENCAPSULATED SILVER-ZINC CELLS FOR DEEP OCEAN APPLICATIONS

By

William A. Birtcher and William E. Heronemus

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CHAPTER I

INTRODUCTION

The amount of meaningful work that a submersible is able to accomplish while submerged is largely dependent upon the quantity of energy that has been stored and can be expended. Generally, electrical energy will be required for the main propulsion and maneuvering motors, for running various pumps, for maintaining communications, for supplying external lighting, and for operating manipulators. Unless the DSV uses an umbilical link to a surface type support facility, it must carry its own energy storage subsystem. The length of a mission for any given task, or the full speed search range is thus limited by the size and number of the storage cells that a boat can accommodate.

There are several ways in which these cells can be carried. The earliest method, and one which is still used extensively today, involves placing lead-acid storage batteries within the personnel hull of the boat. (Reference 3). Several disadvantages of such an arrangement are obvious. The amount of energy to be stored is limited by the size of pressure hull and the number of embarked personnel. Conversely, the size of the crew, the amount of equipment to be carried, the speed of the boat, and the nature and duration of the mission are all dependent upon the amount of stored energy available. In placing the batteries of a boat within

its pressure hull, considerable weight is added with no change in displacement. Also, both the health and safety of the crew could be endangered if inadequate attention is given to the control of gaseous effluents of the lead-acid batteries. An important advantage of this type of energy storage is the ease with which the cells can be serviced, either under normal conditions or in an emergency situation while submerged.

A great advance was made with the development of the pressure compensated battery container. (Reference 24). A sealed container immersed in a fluid experiences a uniform pressure on its outside surfaces proportional to its operating depth. When the pressure differential from the outside to the inside of the container reaches and exceeds the collapse pressure of the container, it will fail. This collapse pressure is a function of the material used in the container, its thickness, and its shape. For operation in the ocean at great depths, a container having thick walls of a heavy material would be needed to withstand the large pressure differential experienced. If the pressure differential could be reduced or eliminated, the container could be constructed of almost any thin, lighweight material.

The principle behind a pressure compensated system is that the sea pressure is transmitted by a flexible membrane through a lightweight fluid and hence to the inside walls of

the container. Thus the inside pressure equals the outside pressure, the pressure differential is zero, and the container can be operated to any depth without collapsing.

Removing the storage batteries from the pressure hull and mounting them in such a pressure compensated compartment eliminates the disadvantages of the system previously mentioned. With this container located in the free flooding void within the outer skin of the boat, its displacement provides some buoyancy to help offset the weight of the cells. The crew is not jeopardized and the energy storage capacity of the boat can be enlarged by enlarging the pressure compensated compartment to hold more cells.

Placing the storage cells in a sealed, fluid-filled container mounted external to the personnel hull does not allow for easy access to them in the event of a malfunction. Another feature of this type of energy storage system is that the overall weight to displacement ratio exceeds 1.0, necessitating the addition of floatation material to achieve neutral buoyancy.

The development of lightweight, high energy density batteries such as silver-zinc cells made possible the reduction of the weight to displacement ratio, though not below 1.0. (Reference 2). Also, neither the reliability of the pressure compensated silver-zinc system nor its performance has been as good as expected due to the cell's behavior in a fluid under pressure. (Reference 16).

If the cells could be protected in pressure-proof housings, eliminating the fluid medium, these difficulties would be overcome. In addition, if the weight of the cells in the pressure vessel was kept smaller than the net buoyancy of the container, an energy storage system capable of positive, neutral, or negative buoyancy would be possible without the need of additional floatation material.

Until recently, such a pressure vessel would have had to be constructed of metal. Metal spheres capable of operating at depths of 15-20,000 feet would have weight to displacement ratios approaching, but greater than 1.0, which make them unsuitable for this application. Within the last few years, glass spheres have become available having weight to displacement ratios of less than 0.5, and with operating depth capabilities of more than 20,000 feet. (Reference 5). The spheres, readily available on the market today, are small, having diameters of about sixteen inches and small entry ports. This size precludes the use of the large lead-acid type batteries, but is well suited for the encapsulation of the smaller silver-zinc cells.

This thesis will concern itself with the development of an electrical storage system capable of achieving positive, neutral, and negative buoyancy utilizing the concept of silver-zinc cells in small pressure-proof glass spheres.

CHAPTER II

LITERATURE REVIEW

Before silver-zinc cells and other high-energy density devices became commercially available (References 6, 17), the lead-acid type storage cell provided the major source of electrical energy for submerged vehicle operation. The biggest user of storage batteries for undersea use has probably been the Navy. The Bureau of Ships Technical Manual's chapter on the electrical plant, power generation, and power distribution (Reference 3) give a thorough treatment of the lead-acid storage system mounted within the pressure hull of a submarine.

That type of system was not well suited for use in DSV's with small pressure hulls. Strohlein (Reference 24) reported in 1968 on a pressure equalization system designed to permit lead-acid storage batteries on submersibles to be carried outside the pressure hull, saving the critical space inside the hull for operators and equipment.

Work by U. S. Navy personnel (References 4,10,18,19) showed the possibility of locating the remaining components of the distribution circuits within a pressure compensated compartment.

The weight of the pressure compensated system was greatly reduced by the use of silver-zinc cells, but Momson and Clerici (Reference 16) reported that the performance and reliability of that type of system was not as good as expected.

The prossure proof silver-zinc system presented in this paper represents the most recent advance made in the area of electric storage battery systems for deep submersibles. This system retains the performance and reliability of the silver-zinc cell and utilizes its light ght to form a storage system capable of positive, neutral, or negative buoyancy.

C H A P T E R III

A SURVEY OF COMMERCIALLY AVAILABLE STORAGE CELLS

There are primarily four types of batteries used in the energy storage systems of deep submergence vehicles. These are the lead-acid, nickel-cadmium, silver-cadmium, and silver-zinc cells. Fuel cells and nuclear reactor power plants are available, but their cost or bulk place them beyond consideration for small DSV's of the type for which this report is intended. (Reference-Pratt & Whitney).

The lead-acid type of storage cell has been the main source of electrical energy for submersibles for many years. Navy submarines rely on lead-acid storage batteries for submerged operation as do many of the smaller DSV's. This type of cell provides a rugged, reliable, and inexpensive storage element that gives good voltage regulation and can undergo many charge-recharge cycles. The weight and large bulk, in addition to the need for adequate ventilation, are the principle disadvantages of the lead-acid battery.

The nickel-cadmium battery has the longest cycle life, but is heavier than the silver-cadmium or silver-zinc batteries. The sealed cells are designed to operate with a low electrolyte level to leave considerable surface for oxygen evolution recombination at the negative (cadmium) electrode. In these cells, oxygen evolution occurs near the charge voltage of the nickel electrode; consequently, the voltage rise

at the end of charge is not sharp and does not clearly indicate completion of charging, particularly at high temperatures. This complicates charge control systems based upon voltage. However, the cells are able to tolerate continuous overcharge levels as long as the oxygen generated during overcharge is not allowed to escape. Main disadvantages of the nickel-cadmium is the difficulty with which the electrical properties can be predicted. To a great extent, the problems involved are inherent in the nature of the chemical system, whose properties vary with the history of the cell in the cycles of operation immediately preceding the measurement being taken.

The silver-cadmium cells have as advantages: energy densities twice that of the nickel-cadmium and cycle life one to two orders of magnitude greater than the silver-zinc cell. They may be charged more rapidly than silver-zinc cells and are useful when rapid repetition of cycles is required. However, they have exhibited low cell voltage and a resultant poor system voltage regulation.

The silver-zinc cell has the highest energy density of the cells discussed here. These cells have a wet stand life up to five years and can undergo 80-100 charge-discharge cycles. Small amounts of hydrogen and oxygen gas may be evolved in the silver-zinc cell during charge, discharge and stand. The electrical characteristics of the silver-zinc

cell are similar to those of the silver-cadmium cell, except that the voltage is higher in the silver-zinc cell and its voltage regulation is better. The ampere-hour efficiency of a silver-zinc system (defined as A-H output/A-H input) under normal operating conditions is close to 100 percent. The watt-hour efficiency (W-H output/W-H input) is about 70 percent under normal conditions. Charging silver electrodes at high rates (65-105 MA/in^2) may result in an ampere-hour efficiency below the normally expected 100 percent.

In order to determine the optimum cell to use in conjunction with small pressure-proof vessels for an energy storage system, inquiries were made to the major manufacturers of storage batteries. Appendix A presents some commercially available storage cells, including lead-acid, nickel-cadmium, silver-cadmium, and silver-zinc cells. Manufacturers are listed alphabetically and their products described.

CHAPTER IV

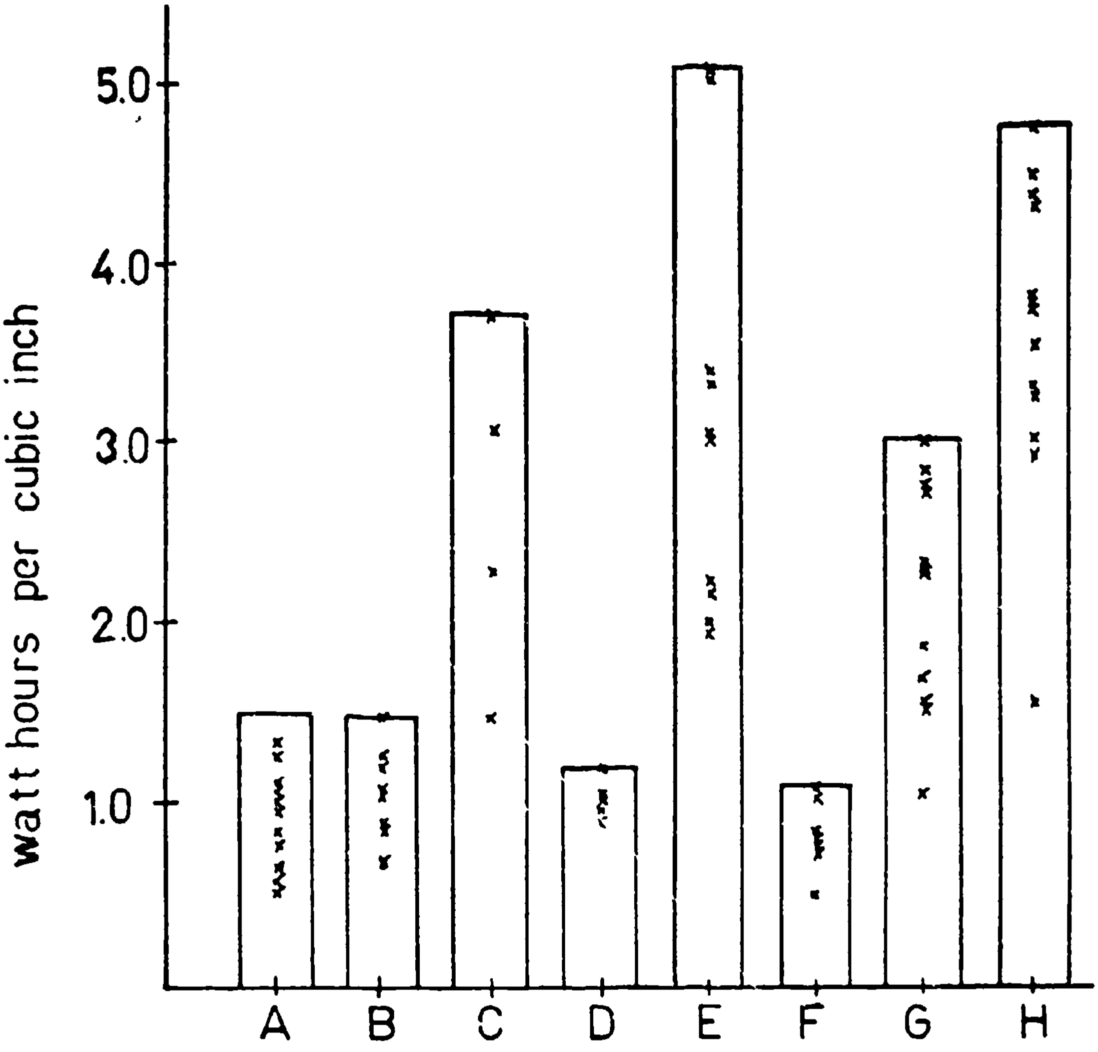
AN INVESTIGATION AND COMPARISON OF AVAILABLE ENERGY STORAGE DEVICES WITH SILVER-ZINC CELLS ON WEIGHT AND SIZE VERSUS STORAGE CAPACITY BASIS

The search for a high energy density storage cell was conducted by means of inquiries to various storage battery manufacturers. (Reference 7, 9, 12,27). The information supplied by those companies that responded was presented in Appendix A. In this chapter, the results of a comparison of the available cells on a weight and size versus storage capacity basis will be presented. The tabulated energy densities are given in Appendix B for convenience and aid in further storage system design work.

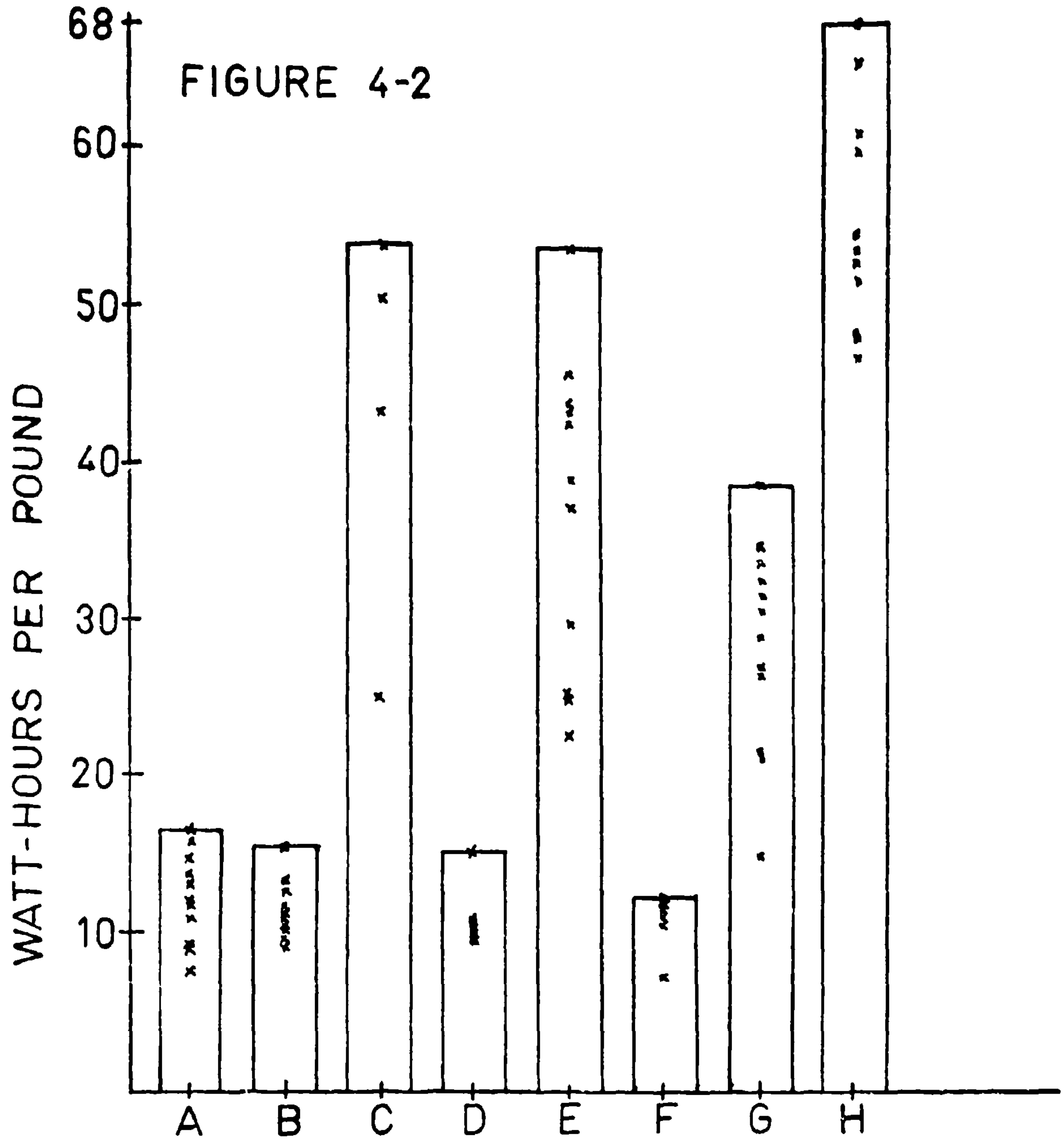
To easily compare the different types and brands of available storage cells, their energy densities are plotted in Figure 4.1 and Figure 4.2. These plots show the advantage of the silver-zinc type storage battery over the lead-acid, nickel-cadmium, and silver-cadmium type cells for both the watt-hours per cubic inch and watt-hours per pound categories.

Figure 4.1 indicates that the Exide silver-zinc cells have higher watt-hours per cubic inch than the Yardney silver-zinc cells. Closer examination, however, reveals that this advantage is due only to one cell, the DS-25. There are eight Yardney silver-zinc cells that have higher watt-hours

FIGURE 4-1 ENERGY DENSITIES



A	Eagle-Picher	vented nickel-cadmium
B	Eagle-Picher	non-vented nickel-cadmium
C	Eagle-Picher	silver-zinc
D	Exide	lead-acid
E	Exide	silver-zinc
F	G.E.	nickel-cadmium
G	Yardney	silver-cadmium
H	Yardney	silver-zinc



A Eagle-Picher vented nickel-cadmium
B Eagle-Picher non-vented nickel-cadmium
C Eagle Picher silver-zinc
D. Exide lead-acid
E Exide silver-zinc
F G.E. nickel-cadmium
G Yardney silver-cadmium
H Yardney silver-zinc

per cubic inch values than the next Exide cell. This would seem to provide a wider base of candidates for selection of an optimum cell for encapsulation in small pressure-proof enclosures.

Since the proposed pressure vessels are small, having only 45.8 pounds of net buoyancy, perhaps the watt-hours per pound values should be given a higher priority than the watt-hours per cubic inch values. The optimum cell will have to have a high watt-hours per pound value so that a reasonable amount of energy can be stored in the individual pressure vessels for each of several cases of differing buoyancy.

Inspection of Figure 4.2 shows that the Yardney silver-zinc cells have the highest values of watt-hours per pound. Five Yardney cells have higher watt-hours per pound values than the best Eagle-Picher or Exide silver-zinc cells.

This wide variety of high energy density Yardney silver-zinc storage cells provided the candidates for encapsulation within small pressure vessels forming the power system to be developed in the following chapters.

CHAPTER V

THE CHARACTERISTICS, BEHAVIOR, REQUIREMENTS, AND ADVANTAGES OF A SILVER-ZINC CELL FOR ENERGY STORAGE

Although this paper is concerned chiefly with the utilization of the silver-zinc cell as a building block for the construction of a complete energy storage system, some details will be given of the electrochemical processes involved. This is primarily a presentation of established properties of the AgZn cell, and is reproduced here only as an aid in the justification of the AgZn cell as the logical choice for a high energy density storage element. The fundamental electrochemical principles underlying AgZn battery operation and many of the operating characteristics of these cells are common to all electrochemical systems. (Reference 22).

The ingredients of the AgZn galvanic cell can react simultaneously. However, these materials are packaged in such a way that the reaction process cannot proceed unless an external circuit is closed, resulting in a mutual oxidation-reduction reaction. This reaction is a chemical change in which there is a transfer of electrons from one reactant to the other. The reactant losing electrons (the zinc electrode) is oxidized, and the one accepting electrons (the silver electrode) is reduced. When these reactants are mixed, under the proper conditions, the reaction occurs

spontaneously with the evolution of heat. However, when these reactants are mounted on current-collecting electrodes and prevented from mixing, immersed in an electrolyte, and connected by an external circuit, the reaction then proceeds at a rate which may be controlled by the circuit's resistance to an electric current. The products of the reaction enter the electrolyte to replace those combined at the electrodes of opposite polarity at which the chemical change is completed. The resulting concentration gradients cause diffusion through the electrolyte.

The electrolyte solution is usually made up of a solution of highly ionizable chemical, such as potassium hydroxide in water. The cell's electric conductivity is directly related to the ionic conductivity of the electrolyte.

The AgZn alkaline cell is characterized by two distinct voltage plateaus on charge and discharge. The reaction occurring at the positive, silver electrode at the lower voltage plateau is

$$\underset{\text{charged}}{Ag_2O + H_2O + 2e^-} \rightleftharpoons \underset{\text{discharged}}{2Ag + 2OH^-} \qquad (5\text{-}1)$$

and that at the higher voltage plateau is

$$\underset{\text{charged}}{2AgO + H_2O + 2e^-} \rightleftharpoons \underset{\text{discharged}}{Ag_2O + 2OH^-} \qquad (5\text{-}2)$$

On charge, the reactions occur in the direction opposite to that written. The reaction at the negative zinc electrode is

$$\begin{array}{ccc} \text{charged} & & \text{discharged} \\ Zn + 2OH^- & = & ZnO + H_2O + 2e^- \end{array} \qquad (5\text{-}3)$$

The zinc oxidation product is highly soluble in a potassium hydroxide solution. The zincate then undergoes very slow decomposition to zinc oxide. This characteristic is considered a major drawback in the zinc electrode since the ionized species must be transported in order to carry current between electrodes. The self-discharge reaction of the electrode may be written

$$Zn + 2OH^- + 2H_2O = Zn(OH)_4^{=} + H_2 \qquad (5\text{-}4)$$

Materials are often added to the silver-zinc couple to modify the reaction chemistry to improve the operating characteristics of the cell. (Reference 23). The two most common additives to zinc electrodes are a mechanical binder and a self-discharge suppressor. Secondary zinc electrodes are usually manufactured in the discharged state, as powdered zinc oxide, to which polyvinyl alcohol is added as a mechanical binder for improving mechanical strength.

The self-discharge reaction (eq. 5-3) is suppressed by raising the hydrogen overvoltage through the addition of

mercury (normally as mercuric oxide added to the zinc-oxide power). The addition of mercury to the zinc electrode has also been used to control the growth of zinc dendrites (long needles of zinc growing through the separator causing short circuits).

Cadmium has been added to the silver electrode to promote gassing protection. It acts to combine the oxygen gas evolved at the zinc electrode, thereby limiting gas pressure building in sealed cells.

The most common additive to the potassium-hydroxide electrolyte is zinc oxide. Zinc oxide forms the zincate ion ($Zn(OH_4)^{=}$) in caustic solution. Normally, sufficient zinc oxide is added to saturate the potassium hydroxide, preventing the zinc oxidation products from entering into the electrolyte solution.

Three processes other than gas evolution are identified as being responsible for the deterioration in performance of the AgZn cell. In operation, the Zn electrode undergoes a change in shape caused by solution and reprecipitation of zinc oxide as the cell cycles between charge and discharge. Due to gravity, these deposits move toward the lower part of the electrode, thickening it, and reducing the total available surface area. This causes a change in current density, an increase in polarization, and a decrease in performance.

Oxides of silver have been shown to dissolve in the electrolyte, forming argentate ions, which, upon contact with the zinc electrode, deposit metallic silver on the zinc. This forms a shorted zinc-silver cell, which then evolves hydrogen gas from the zinc electrode. The usual approach to the prevention of silver deposition on the zinc electrode is the interposition between silver and zinc electrodes of layers of separator designed to prevent the dissolved silver compounds from reaching the negative electrode.

Another of the processes responsible for cell failure in the AgZn cell is the development of short circuits as a result of the growth of zinc dendrites which penetrate the separator.

The electrical characteristics of the AgZn cell are similar to those of the AgCd cell except that the voltage is higher in the AgZn cell. (Reference 2). They (AgZn cells) combine the characteristics of the silver electrode with those of the zinc electrode, which, in spite of its solubility problems, is electrochemically reversible. The open-circuit potentials of the upper and lower plateaus of the AgZn cell are 1.86 V and 1.60 V, respectively. The charging and discharging characteristics can vary considerably, depending upon the structure of the electrodes, the number of layers and type of materials used in the separator, the concentration of KOH in the electrolyte, and other factors.

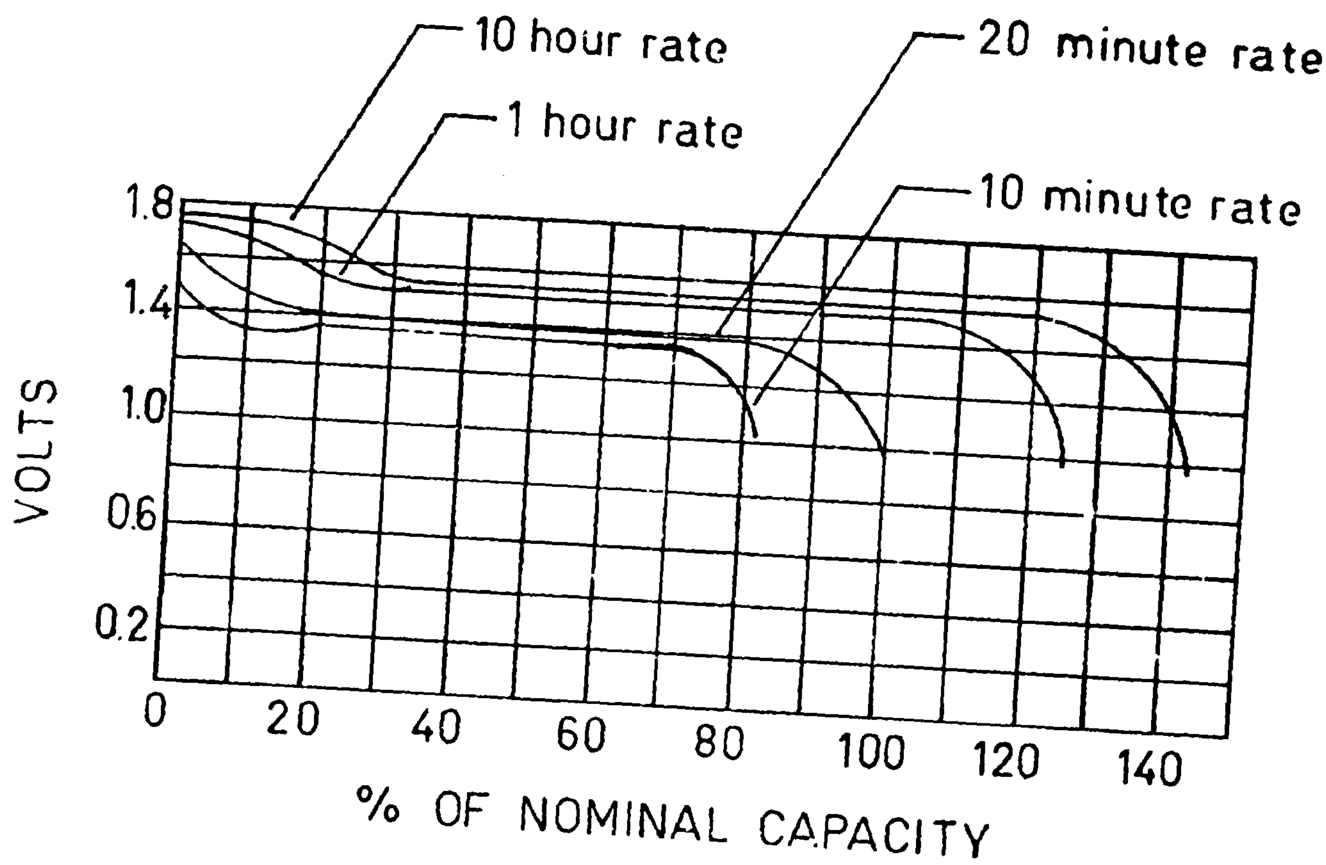


FIGURE 5-1 TYPICAL DISCHARGE CURVES FOR SILVER-ZINC CELLS[19]

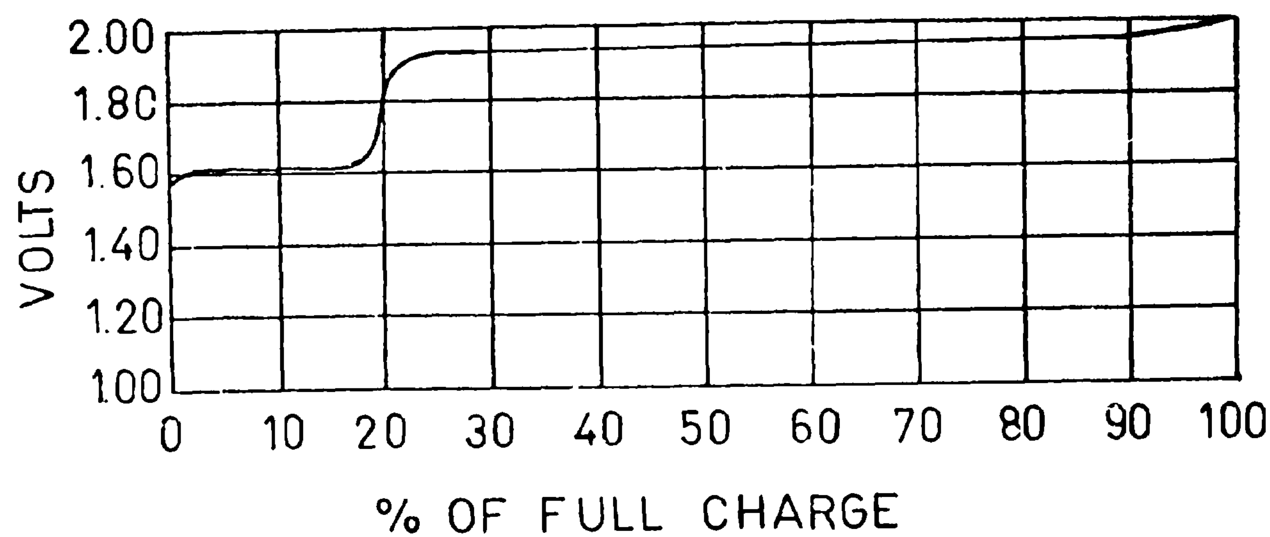


FIGURE 5-2 TYPICAL CHARGE CURVE FOR SILVER-ZINC CELLS

The ampere-hour efficiency of the AgZn system (defined as A-h output/A-h input) under normal operating conditions is close to 100%. The watt-hour efficiency (W-h output/W-h input) is about 70% under normal operating conditions because of the difference between the charge and discharge polarization potentials. Charging silver electrodes at high rates (65-100 mA/in^2) may result in reduced amp.-hr. efficiency. During stand periods, activated AgZn cells lose energy by self-discharge. During extended periods of time, a decomposition reaction occurs as follows:

$$2AgO = Ag_2O + 1/2O_2 \ .$$

Since divalent silver is converted to monovalent, the duration of the upper plateau decreases. Where stand times are short, and the electrolyte has not had sufficient time to penetrate the separator completely, low voltages may occur as a result of [illegible] internal resistance. As the cell discharges, the [illegible]lyte penetrates the separator and electrodes, and th[illegible] heats internally, increasing voltage output. It appears that the effects of stand time are not entirely consistent, suggesting that other experimental variables may be affecting electrical characteristics. Impedance of AgZn cells is not often reported. The lack of data is due to the reported difficulty of obtaining repeatable measurements. No adequate impedance data as a function of frequency

or of state of charge were found although this could perhaps be obtained from performance curves.

Service life of a AgZn cell is affected by the separator system, depth of discharge, temperature, and electrolyte concentration. Battery degradation, and thus service life, starts when the electrolyte is added. Deterioration of separator and dissolution of the negative electrode begin immediately and continue with time, regardless of cycle life, until end-of-service life.

Charging of AgZn cells should be accomplished by use of a modified constant potential type charger consisting of a voltage regulator and current limiter in series with the battery. To prevent premature battery failure, two basic constraints must be imposed during charging of silver-zinc batteries. The polarization of the zinc electrode must be limited to less than 100 mv to avoid formation of zinc dendrites. The voltage must be limited to a value of approximately 1.96 volts/cell at room temperature to avoid generation of excessive quantities of oxygen gas. After the cell has been fully charged, and if its use is not anticipated for a long period of time, charging should be terminated and the cell returned to charge a few hours prior to its expected use.

The advantages of the AgZn cell over the AgCd, NiCd, Pb-acid, and NiFe types can be readily demonstrated. (Reference 17). The light weight, small size, and high storage

capacity of the AgZn cell give it much higher energy density values than the other types of storage cells. The AgZn cell retains its charge longer, and exhibits better voltage regulation then the other cells.

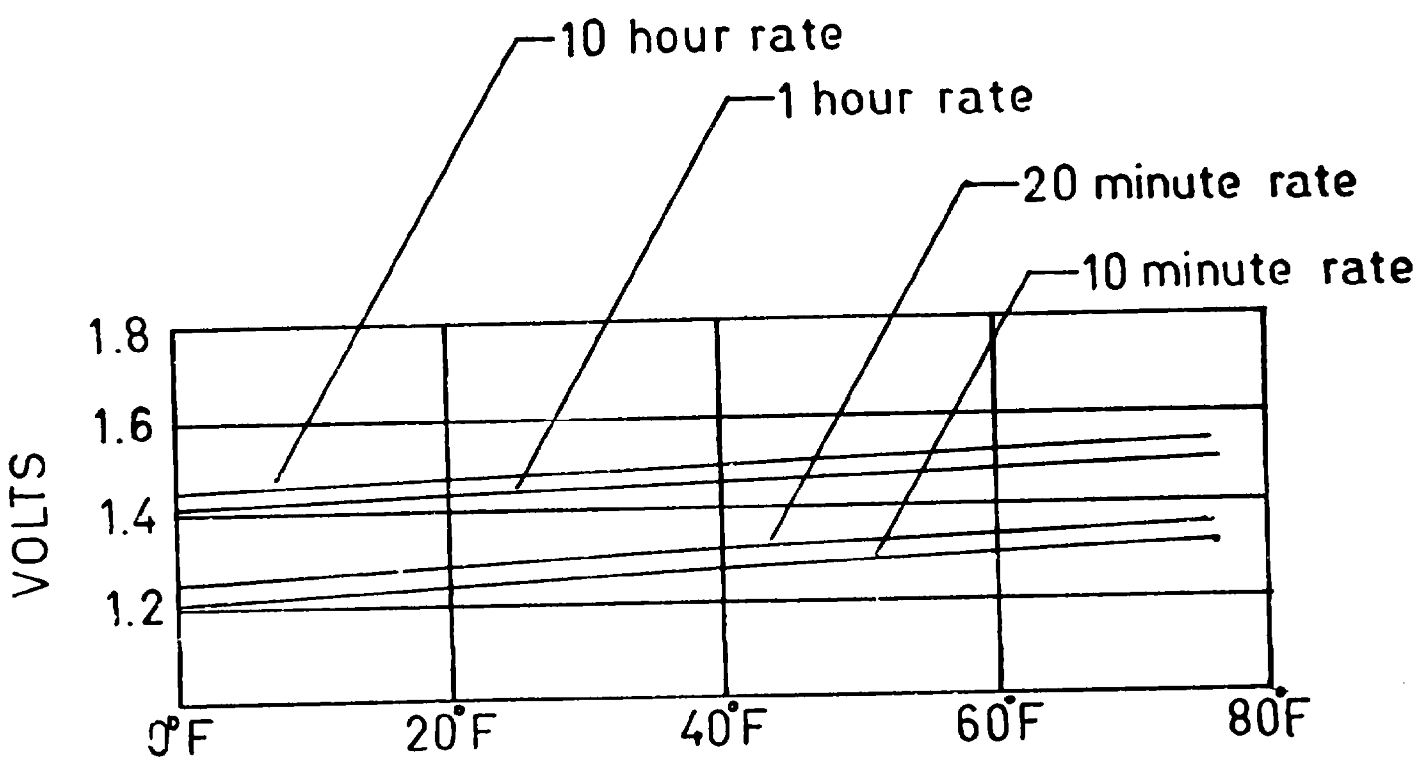


FIGURE 5-3 TEMPERATURE EFFECT ON PLATEAU VOLTAGE

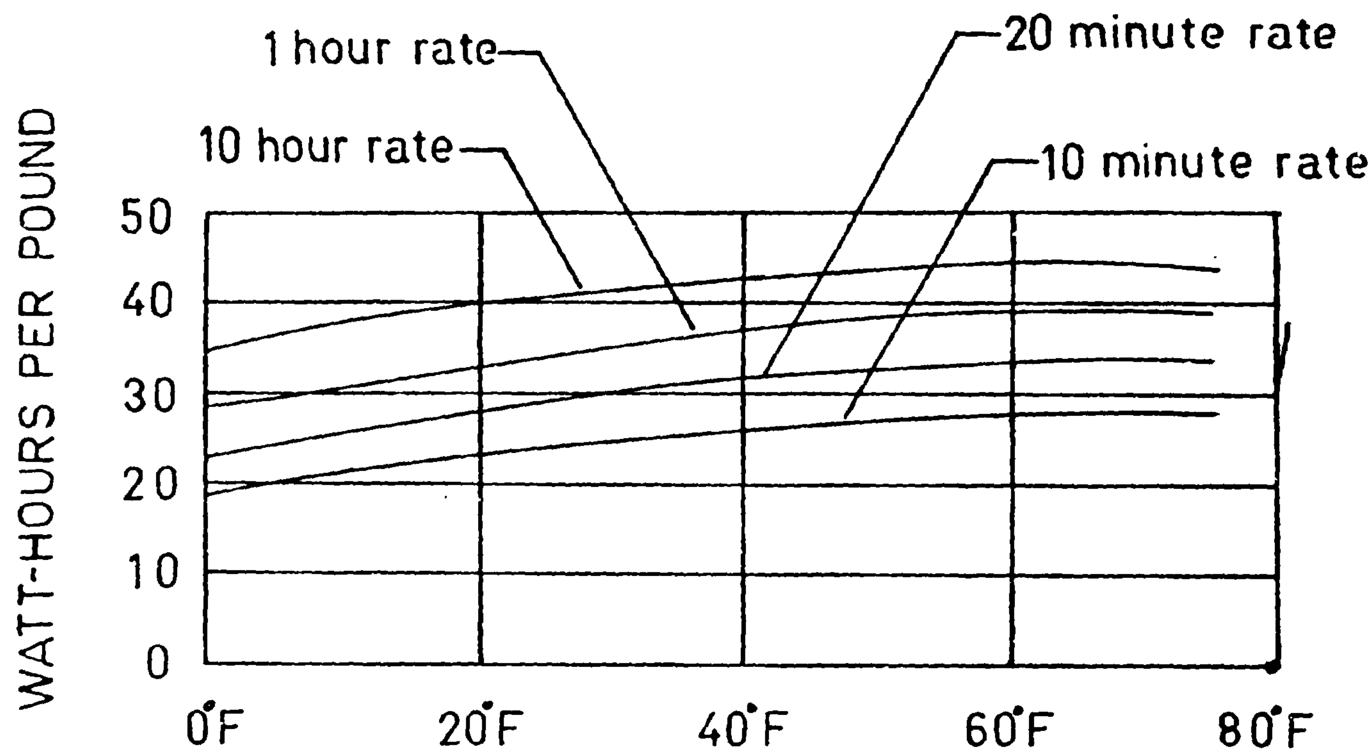


FIGURE 5-4 TEMPERATURE EFFECT ON ENERGY DENSITY

CHAPTER VI

DESIGN CONCEPTS UTILIZING THE SILVER-ZINC CELL AS THE STORAGE ELEMENT ENCAPSULATED IN SMALL PRESSURE-PROOF VESSELS FOR NEGATIVE, NEUTRAL, AND POSITIVE BUOYANCY CONDITIONS

The concept of placing storage batteries in pressure-proof enclosures is not new. Lead-acid batteries have been stored in large, heavy pressure-proof steel spheres with some success. The weight and bulk of such an arrangement present something of a problem to the naval architect, whose job it is to balance a boat to neutral buoyancy and an even trim, while retaining a fair and efficient hull form.

Two designs presented by Heronemus in "Some Alternative Lead-Acid and Silver-Zinc Energy Storage Subsystems for 10,000-20,000 Foot Operating Depth DSV's" (Reference 13) show the desirability of using a material other than steel for the pressure-proof enclosure. Both designs are for an operating depth of 20,000 feet and use 42 Exide 3-DFH-17 lead-acid batteries as the storage element. (Reference 9). This provides a storage capability of 45.36 KWH for each system. Primary difference between the two systems is that one uses a steel sphere while the other uses a glass one for the pressure vessel.

The first design uses a steel pressure-proof sphere.

Design I - 20,000 foot operating depth, 42 lead-acid cells inside one 53" ID HY 100 sphere. 45.36 KWH.

Item	Weight	Displacement	Cost
1. 53" ID Sphere	4,700#	3,570#	$28,200
2. flanges & fasteners	40	6	200
3. 42 cells	2,520	-----	5,040
4. stacking flats	100	-----	200
5. battery cell monitor	20	-----	1,500
6. disconnect plugs	35	-----	200
Totals	7,415#	3,576#	$35,340
38 PCF foam to achieve $\frac{W}{\Delta} = 1.0$ (147.7 ft.^{3})	5,613	9,453	23,570
Totals	13,028#	1-,029#	$58,910

$$\text{Watt-hours per \$} = \frac{45,360 \text{ WH}}{\$58,910} = 0.77$$

$$\text{Watt-hours per lb.} = \frac{45,360 \text{ WH}}{13,028 \text{ lb.}} = 3.48$$

$$\text{Watt-hours per ft.}^3 = \frac{45,360 \text{ WH}}{55.8 \text{ ft.}^3} = 813$$

The second design uses a glass pressure-proof sphere.

Design II - 20,000 foot operating depth. 42 lead-acid cells inside one 53" ID glass sphere. 45.36 KWH.

Item	Weight	Displacement	Cost
1. 53" ID glass sphere	1,125#	2,750#	$ 4,000
2. equatorial ring & penetrators	120	25	500
3. 42 3-DFH-17 cells	2,520	-----	5,040
4. stacking flats	100	-----	200
5. battery cell monitor	20	-----	1,500
6. disconnect plugs	35	-----	200
Totals	3,920#	2,775#	$11,440
38 PCF foam to achieve $\frac{W}{\Delta} = 1.0$ (44.03 ft.^{3})	1,672	2,816	7,022
Totals	5,592#	5,591#	$18,462

$$\text{Watt-hours per \$} = \frac{45{,}360 \text{ WH}}{\$18{,}462} = 2.46$$

$$\text{Watt-hours per lb.} = \frac{45{,}360 \text{ WH}}{5{,}592 \text{ lb.}} = 8.14$$

$$\text{Watt-hours per ft.}^3 \quad \frac{45{,}360 \text{ WH}}{43 \text{ ft.}^3} = 1{,}050$$

In comparing these two systems, electrically identical, it can be seen that by using a glass pressure vessel, rather than a steel one, the watt-hours per dollar value is increased by a factor of 3.2, and the watt-hours per pound increased by a factor of 2.34. This lighter weight glass sphere system still poses essentially the same problems to the submersible designer as did the steel sphere system. Although the desirability of a container material lighter than steel is demonstrated, the need for smaller packaging arrangements is also indicated.

The next step in this progression towards a desirable energy storage system was the investigation of individually packaged lead-acid cells, namely the Exide 3-DFH-17. This cell is considered because it has the highest energy density of the lead-acid batteries available. It weighs 60 pounds and can store 1.08 KWH of energy, resulting in 18 watt-hours per pound.

The minimum size of a sphere that will hold a rectangular object such as a 3-DFH-17 cell is one whose diameter is equal to the length of the major diagonal of the battery. The length of this diagonal for the 3-DFH-17 battery is 16.2". A sphere of HY-80 steel was designed (see Appendix C) having an inside radius, r_i = 8.1". For an operating depth of 20,000 feet, the thickness, h, required was slightly more than one inch. The sphere weighed 270# and displaced 120#. Estimated cost for off-the-shelf spheres is approximately $250 each.

The third design has the following characteristics:

Design III - 20,000 foot operating depth, 42 lead-acid cells individually packaged in steel spheres. 45.36 KWH.

Item	Weight	Displacement	Cost
1. 42 spheres	11,340#	5,040#	$10,500
2. 42 batteries	2,520	-----	5,040
3. stacking flats	100	-----	200
4. cell monitor	20	-----	1,500
5. disconnect plugs	35	-----	200
Totals	14,015#	5,040#	$17,440
38 PCF foam to achieve $\frac{W}{\Delta} = 1.0$ (345.2 ft.^{3})	13,118	22,093	55,096
Totals	27,133#	27,133#	$72,536

$$\text{Watt-hours per \$} = \frac{45{,}360 \text{ WH}}{\$72{,}536} = 0.625$$

$$\text{Watt-hours per lb.} = \frac{45{,}360 \text{ WH}}{27{,}133 \text{ lb.}} = 1.67$$

$$\text{Watt-hours per ft.}^3 = \frac{45{,}360 \text{ WH}}{424 \text{ ft.}^3} = 1{,}070$$

This system has lower watt-hours per dollar and watt-hours per pound values than even the large steel sphere system. Its only redeeming feature would seem to lie in the ease with which these smaller spheres could be installed in the boat, utilizing what before might have been useless voids within the outer skin of the craft.

What these designs seem to indicate is the need for lighter, more buoyant, individual pressure-proof containers. The next concept explored was that of enclosing the lead-acid cells in cast, foam spheres. The syntactic foam investigated by the author (Reference 8) was found to have a yield strength of 10,000 psi. If the allowable stress is held to 2/3 of the yield strength, then this material is restricted to operating depths of less than 15,000 feet. Several foam spheres were designed for depths up to 15,000' (see Appendix D). These would appear to be promising for shallow depth boats, but since interest here is for boats of 20,000 foot capability, they were disregarded.

Having decided that the energy storage system should be broken down into smaller, individually packaged, pressure-proof units, and that these pressure-proof containers should not be made of either metal or foam, glass spheres were once again considered.

A suitable glass sphere for enclosing the 3-DFH-17 battery was not found. The requirements of the sphere were

(a) inside diameter of 16.2", (b) equatorial flange and gasket or opening large enough to permit access to a 3-DFH-17 battery, (c) capability for establishing electrical penetrations, (d) 20,000 foot operating depth. Inquiries to several glass companies revealed that Corning Glass Company manufactures several small glass spheres capable of operation to 20,000 feet. The largest off-the-shelf sphere, however, is their Model C-16, Glass Instrument Housing. (Reference 5). This sphere has a 15" inside diameter and a 4" diameter entry port. It weighs 37.5 pounds while displacing 83.3 pounds.

The small size of this sphere and its polar opening preclude the use of the large lead-acid type battery. The sphere occupies a volume of 1.3 ft.^{3}.

It was at this point that a search was made for a small, lightweight, rechargeable cell with high energy density. It was this investigation and subsequent comparison that led to the selection of the Yardney Silvercel$^{(R)}$. These cells have energy densities of 40-66 watt-hours per pound and 2.5-4.5 watt-hours per cubic inch. Typical number of complete charge-discharge cycles obtainable before output drops to 80% of nominal capacity is 80-100 cycles. Table 6.1 gives typical application data and physical characteristics of the Yardney Low-Rate (LR) Silvercel$^{(R)}$ Models.

Table 6.1 - Application data supplied by Yardney Electric Corp. for their silver-zinc storage cells.

Cell Model	LR-20	LR-21	LR-40	LR-58	LR-60	LR-70	LR-85	LR-90	LR-100
amp. hour output	30.0	30.0	46.0	90.0	65.0	80.0	140.0	145.0	110.0
av. voltage	1.50	1.53	1.52	1.52	1.52	1.50	1.53	1.52	1.51
WH per lb.	51	47	49	66	55	48	55	61	60
WH per in.3	3.0	3.3	3.1	4.4	3.4	3.7	4.5	4.1	3.6
max. wt. (oz)	14.0	15.5	23.0	31.8	29.0	40.0	62.0	57.1	44.0
overall height (in.)	4.28	7.53	7.09	7.25	4.50	6.25	9.44	7.06	4.81
width (inches)	2.05	2.30	3.25	3.25	2.73	2.64	2.81	3.26	[illegible].44
depth (inches)	1.73	0.80	0.99	1.27	2.36	1.41	1.81	2.16	2.78

These nine cells were the candidates for encapsulation within the Corning Model C-16 glass spheres. It was thought that a number of these cells could be packaged within a sphere, thus making an individual battery "jar". A large quantity of these jars could then be interconnected to form a complete energy storage system. By varying the number of Silvercels(R) within a sphere, a weight to displacement ratio could be obtained that could range from a negatively to a positively buoyant value.

In the design of a deep submergence vehicle to operate at depths of 20,000 feet, the weight of the various component parts usually exceeds their displacement. In order to achieve a neutrally buoyant condition, a material that is positively buoyant is added to balance the boat and to obtain an even trim. Syntactic foam, such as Emerson and Cumming's Eccofloat(T) PC 69, is commonly used for this purpose. This foam is made up of glass microspheres embedded in an epoxy resin. A cube of PC69, one foot on each side, would weigh 42 pounds, while displacing 64 pounds in salt water. Therefore, the weight to displacement ratio of this floatation material is 0.656; it is positively buoyant.

If the Silvercels(R) could be arranged within the Corning C-16 sphere in such a manner that its overall weight to displacement ratio would be 0.656, then the battery jar could be substituted directly for floatation foam in an

existing DSV. This would increase the total energy storage capability of the craft without changing its physical dimensions or effecting its trim or balance.

By packaging the correct number of Silvercels(R) in the C-16 sphere to achieve a weight to displacement ratio of 1.0, these jars could be installed in any free-flooding voids within the outer skin of a boat. This would increase the overall energy storage capacity of the boat while increasing the payload to displacement efficiency. Again, the major dimensions and balance of the boat are unaffected.

A third case should be considered here, that of a weight to displacement ratio greater than 1.0. A Case III battery jar would be filled with as many cells as would physically fit, regardless of the resultant weight.

The idea of encapsulating Silvercels(R) within Corning Model C-16 glass spheres was the last step in the development of a lightweight, versatile energy storage system. The system would be available in any of three cases of weight to displacement values, namely:

Case I Positively buoyant, $\frac{W}{\Delta} = 0.656$ (imitation foam)

Case II Neutrally buoyant, $\frac{W}{\Delta} = 1.00$

Case III Negatively buoyant, $\frac{W}{\Delta} > 1.0$ (fully loaded)

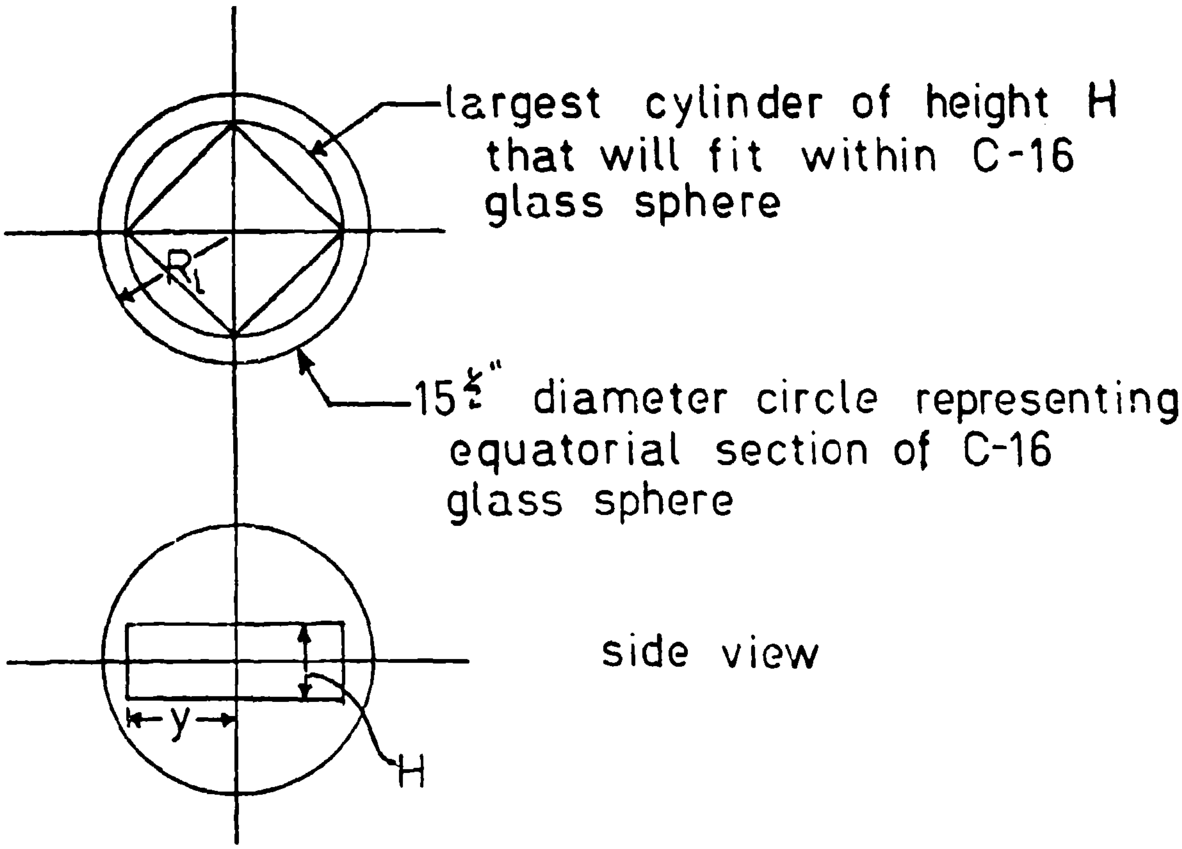
The first step in the development of each of these cases was the determination of which of the nine candidate cells would fit through the 4" diameter polar opening in the C-16

sphere. This was accomplished by calculating the length of the diagonal of the base of each of the nine cells. These values are presented in Table 6.2.

Table 6.2 - Physical dimensions supplied by Yardney Electric Corp. for their silver-zinc storage cells.

Cell Model	LR20	LR21	LR40	LR58	LR60	LR70	LR85	LR90	LR100
wdth.(in.)	2.05	2.30	3.25	3.25	2.73	3.64	2.81	3.26	3.99
depth.(in.)	1.73	0.80	0.99	1.27	2.36	1.41	1.81	2.16	2.78
diag.(in.)	2.68	2.44	3.40	3.48	3.62	3.90	3.34	3.91	4.41

Investigation of Table 6.2 indicated that the Model LR-100 Silvercel(R) would not pass through the opening in the Corning C-16 sphere, thus reducing the number of candidate cells to eight. The next step in selecting the optimum Silvercel(R) to use for each of the three cases of differing buoyancy was to determine how many of each model Silvercel(R) would fit within the C-16 glass sphere. This was accomplished by calculating the largest cylinder that would fit into the C-16 sphere as a solid section whose height was equal to that of an individual cell, and whose centroid coincided with the centroid of the sphere. Since the candidate cells were of differing heights, there would be a different size cylinder for each model. In some cases there was room for two layers of cells. The geometry used in calculating the size of the squares is illustrated in Figure 6.1.



Where, H is overall height of cells
R_i is inside radius of sphere , 7.5"
y is radius of cylinder

FIGURE 6-1 GEOMETRY USED IN CALCULATING MAXIMUM CYLINDERS TO FIT WITHIN C-16 GLASS SPHERE

The geometrical relationship obtained from Figure 6.1 is

$$\left(\frac{H}{2}\right)^2 + y^2 = R_i^2$$

where H is the overall height of cells (including terminals) y is radius of largest cylinder of height H that can be inscribed in a C-16 sphere. R_i is inside radius of sphere 7.5". Solving for y, and inserting the value of R_i, gives

$$y = \sqrt{56.25 - \left(\frac{H}{2}\right)^2}$$

Table 6.3 gives the values of y, the radius of the largest cylinder of height H which can be inscribed within the C-16 sphere, for each of the eight candidate cells. Two values are given for the Model LR-60 and LR-20 Silvercels(R) since either one or two layers of these cells can be accommodated in the sphere.

Table 6.3

Cell Type	LR-20	LR-21	LR-40	LR-58	LR-60	LR-70	LR-85	LR-90
H	4.28	7.53	7.09	7.25	4.50	6.25	9.44	7.06
$[R_i^2 - (\frac{H}{2})^2]$	51.67	42.0	43.65	43.07	51.24	46.52	33.07	43.89
y_1	7.19	6.48	6.60	6.55	7.15	6.8	5.75	6.62
y_2	6.0				6.0			

The maximum number of Silvercels(R) that would fit within the cylinder of radius, y, was next determined. This was done through the use of scale drawings of the cylinders and cells. Appendix E shows the packing arrangements selected to accommodate the maximum number of Silvercels(R) in the cylinder corresponding to the height of a particular cell model. Table 6.4 gives the stored energy capacity for each of the various cell configurations as well as the weight of the cells and resultant package. Also tabulated are the watt-hours per pound, watt-hours per dollar, and the weight to displacement ratio figures for each cell model system.

Examination of the data presented in Table 6.4, reveals that the buoyancy conditions previously described for Case I and Case II systems were not achieved in four instances. Even if the maximum number of cells that would physically fit were placed within the C-16 glass sphere, additional weight would need to be added to achieve neutral or negative buoyancy for the LR-20, single or double layer, and for the LR-60 single or double layer configuration. The buoyancy condition required for Case I systems $w/\Delta = 0.656$ can be obtained for each cell model by reducing the number of cells carried within the sphere.

Table 6.4 - System Characteristics for Fully Loaded Spheres

Cell Type	LR-20		LR-21	LR-40	LR-58	LR-60		LR-70	LR-85	LR-90
	1 layer	2 layers				1 layer	2 layers			
max. no. of cells in sphere	32	44	56	32	24	16	24	20	14	14
total weight of cells - lbs.	28.0	38.5	54.25	46.0	47.7	29.0	43.5	50.0	54.25	49.96
storage capacity of sphere - WH	1440	1980	2520	2208	3240	1560	2340	2400	2940	3045
total weight of system*	70.5	81.0	96.75	88.5	90.2	71.5	81.0	92.5	96.75	92.5
cost per cell-$	32.25	32.25	32.25	47.80	68.65	71.15	71.15	83.50	103.65	105.35
total cost of system** - $	1390	1750	2140	1890	1950	1470	2040	2000	1780	1905
w/ft.^{3} ratio	0.846	0.97	1.16	1.06	1.08	0.858	0.96	1.11	1.16	1.11
WH/#	20.4	24.4	26.0	25.0	35.9	21.8	28.9	25.9	30.4	33.0
WH/$	1.1	1.13	1.18	1.17	1.66	1.06	1.15	1.2	1.65	1.60
buoyancy condition P, N, Neg.	P	P	Neg	Neg	Neg	P	P	Neg	Neg	Neg

P - positive w < 83.3#
N - neutral w = 83.3#
Neg. - negative w > 83.3#

* includes support for cells, wiring, connectors, etc. - about 5#.

** based on fixed price of $325 for sphere, $5 for support.

As indicated earlier, the Corning C-16 glass sphere weighs 37.5 pounds and displaces 83.3 pounds in salt water. The payload capability of the sphere will be different for each of the three cases of differing buoyancy conditions. Table 6.5 gives these payload capabilities for a new buoyancy of 45.8 pounds per sphere.

Table 6.5 - Payload capability of C-16 glass sphere

	W/Δ	Allowable Payload	System Wt.
Case I	0.656	17.1#	54.6#
Case II	1.0	45.8#	83.3#
Case III	> 1.0	> 45.8#	> 83.3#

In order to select the optimum cell for each of the three systems of differing buoyancy conditions, the cases will be considered separately, beginning with Case I. Table 6.5 indicates that the total available payload for a weight to displacement ratio of 0.656 is 17.1 pounds. Included in this amount is the weight of the cells, the weight of the foam support, and the weight of the inter-cell wiring. A single estimate will be made for these last two items to cover all of the various cell configurations, and a check will be made to see how many cells can be carried to complete the payload capability.

The foam support will be made from syntactic foam weighing 4 PCF. The weight of the support is estimated at 0.5 pounds. Approximately 0.5 pounds of wire and connectors will be used to hook up the cells within the sphere. Therefore, it is estimated that 1.0 pounds of the available payload will be accounted for by these items, leaving room for 16.1 pounds of batteries to achieve a Case I buoyancy condition. The number of cells that can be carried without exceeding this weight allowance is presented in Table 6.6. Also shown are the system characteristics for this Case I buoyancy condition.

Table 6.6 - Case I Configuration; System wt. = 54.6
System Δ = 83.3

Cell Model	LR-20	LR-21	LR-40	LR-58	LR-60	LR-70	LR-85	LR-90
single cell cap. (AH)	30	30	46	90.0	65	80.0	140	145
single cell wt. (oz.)	14.0	15.5	23.0	31.8	29.0	40.0	62.0	57.1
single cell cost - $	32.25	32.25	47.80	68.65	71.15	83.50	103.65	105.35
number in 16.1 lbs. (258 oz.)	18	16	11	8	8	6	4	4
total cell wt.-lbs.	15.7	15.5	15.8	15.9	14.5	15.0	15.5	14.3
wt.needed for ballast	0.4#	0.6#	0.4#	0.2#	1.6#	1.1#	0.6#	1.8#
energy storage cap.WH	810	720	760	1080	780	720	840	870
system cost $325/sph.)	905	840	851	875	895	825	740	746
WH/$	0.895	0.856	0.892	1.23	0.872	0.872	1.13	1.16
WH/lb.	14.8	13.2	13.9	19.8	14.3	13.2	13.5	15.9

The results of Table 6.6 indicate that the optimum combination for a Case I system would be eight Yardney Model LR-58 Silvercels(R) housed in a Corning Model C-16 sphere.

The second system under consideration will be for a Case II buoyancy condition. Table 6.5 indicates that the total available payload for a weight to displacement ratio of 1.0 is 45.8 pounds. Also included in this amount is the weight of the foam support and the weight of the inter-cell wiring. A single estimate will be made for these two items to cover all of the various cell configurations, and a check will be made to see how many cells of each type can be carried without exceeding the allowable payload.

The foam support will be made from syntactic foam weighing 4 PCF. The weight of the support is estimated at 1.0 pound. Approximately 1.0 pounds of wire and connectors will be used to hook up the cells within the sphere. It is therefore estimated that 2.0 pounds of the available payload will be accounted for by these two items, having 43.8 pounds for batteries to achieve a Case II buoyancy condition. The number of cells that can be carried under these conditions is presented in Table 6.7. System characteristics for the different cell models are also given.

Table 6.7 - Case II Configuration, System wt. = 83.3
System Δ = 83.3

Cell Model	LR-20	LR-21	LR-40	LR-58	LR-60	LR-70	LR-85	LR-90
single cell cap. (AH)	30.0	30.0	46.0	90.0	65.0	80.0	140.0	145.0
single cell wt. (oz.)	14.0	15.5	23.0	31.8	29.0	40.0	62.0	57.1
single cell cost - $	32.25	32.25	47.80	68.65	71.15	83.50	103.65	105.35
no.cells in 43.2 lbs. (700.8 oz.)	50	45	30	22	24	17	11	12
no.that will fit in sphere	44	56	32	24	24	20	14	14
total cell weight #	38.5	43.6	43.1	43.7	43.5	42.5	42.6	42.8
ballast weight #	5.3	0.2	0.7	0.1	0.3	1.3	1.2	1.0
total storage cap.WH	1980	2025	2070	2970	2340	2040	2310	2610
system cost ($325/sph.)	$1745	$1775	$1760	$1835	$2035	$1745	$1465	$1595
WH/$	1.13	1.14	1.17	1.62	1.15	1.17	1.57	1.63
WH/#	23.8	24.4	24.8	35.6	28.1	24.5	27.7	31.4

Table 6.7 indicates that the optimum combination for a Case II system would be twenty-two Yardney Model LR-58 Silvercels(R) housed in a Corning Model C-16 glass sphere.

The final system for Case III buoyancy condition has already been described in Table 6.4. This table presents the characteristics of systems that contain the maximum number of cells that will physically fit into the C-16 sphere. Examination of this data reveals that the optimum combination for a Case III system would be twenty-four Yardney Model LR-58 Silvercels(R) housed in a Corning Model C-16 glass sphere.

The three optimum systems can be summarized as follows:

	Case I	Case II	Case III
w/Δ ratio	0.656	1.00	1.08
Yardney Sil-vercel Model	LR-58	LR-58	LR-58
no. of cells used	8	22	24
system cost	$875	$1835	$1950
system wt.	54.6#	83.3#	90.2#
system stor-age cap.	1080 WH	2970WH	3240WH
WH/$	1.23	1.62	1.66
WH/lb.	19.8	35.6	35.9
WH/ft.^{3}	830	2280	2500

After the optimum cell arrangements have been found for the three cases of differing buoyancy, the next step in the progression towards a completed system is the determination of the inter-cell wiring. Since each case utilized a different number of cells, they will be handled separately.

The Case I system incorporates eight Yardney Model LR-58 Silvercels$^{(R)}$ for its energy storage. Each cell has an operating voltage of 1.5 volts and an ampere-hour output of 90 ampere-hours at the 10-hour discharge rate. The recommended 10-hour discharge rate is 9.0 amps. Accordingly, it will be assumed that the cells will be operated at this rate and the intercell wiring designed for a 100% overload capability of 18.0 amperes. A single conductor wire of size AWG #18 is sufficient for this application.

The original idea behind this system was that a battery jar be directly substituted for 1.3 ft.^{3} of floatation material and be compatible with any existing energy storage system. By wiring the Silvercels(R) in various series-parallel combinations, four operating voltages are available. These are 12 volts, 6 volts, 3.0 volts, or 1.5 volts. Connecting all eight cells in series would make the battery jars compatible with any system using a standard 12-volt, lead-acid, automotive type battery. Since many of the existing boats use the Exide 3-DFH-17 lead-acid, 6.0 volt battery, the design presented here will feature two parallel groups of four cells each. The four cells of each group will be connected together in series to give a jar operating voltage of 6.0 volts, and a current drain capability of 18.0 amps. at the 10-hour rate. The cable used for connecting each jar with the existing system or with each other should be a two-conductor underwater cable whose conductors are size AWG #12 to provide a 100% over-rating capability. A cable such as Boston Insulated Wire's, Power and Control Two Conductor Underwater Cable, part #7222-H-002, meets these requirements.

The system selected for the Case II buoyancy conditions poses a bit harder problem in selecting a jar operating voltage. The twenty-two cells of the optimum system can be interwired in only three ways in a symmetric series-parallel combination. These are: (1) all 22 cells in series, operating voltage 33.0 volts; (2) two parallel groups of 11 cells

each, operating voltage 16.5 volts; (3) all 22 cells in parallel, operating voltage 1.5 volts. None of these options is compatible with an existing system using 6.0 volt batteries.

It was decided at this point to select another model Silvercel(R) for the Case II system. Re-examination of Table 6.7 showed that the Model LR-90 arrangement had a larger watt-hours per dollar value than the Model LR-58 system, and was only about 10% below that system in the watt-hours per pound category. Most important, its complement of twelve Silvercels(R) could easily be connected to provide a jar operating voltage of 6.0 volts. The desired operating voltage is obtained by wiring in parallel three groups of four cells each. This provides a current drain capability of 27.0 amperes at the 10-hour rate. The cable used for connecting these jars together or for connecting them with an existing system should be a two-conductor underwater cable whose conductors are size AWG #8, to provide a 100% over-rating capability. A cable such as Boston Insulated Wire's, Power and Control, Two Conductor Underwater Cable, part #7742-H-002, meets these requirements.

The optimum system selected for Case III buoyancy conditions carries twenty-four cells, which can be easily connected to provide a jar operating voltage of 6.0 volts. This operating voltage can be obtained by wiring in parallel, six groups of four cells each. This provides a current drain capability of 54.0 amperes at the 10-hour rate. The cable

used for connecting these battery jars together or for connecting them with an existing system should be a two-conductor underwater cable whose conductors are size AWG #4, to provide a 100% over-rating capability. A cable such as Boston Insulated Wire's, Power and Control, Two Conductor Underwater Cable, part #8032-H-002, meets these requirements.

To bring power leads out of the Corning C-16 glass sphere, modifications were made to the top hatch and clamping mechanism. A Marsh and Marine Type RM'S' 25 BCL (stainless steel) Bulkhead Pigtail Connector (Reference 25) was fitted to a stainless steel hatch covering. The connector has two standard silver plated bronze pins and carries a 50 ampere rating. Attached to the low pressure side of the connector will be a Marsh and Marine standard cable, catalog #B-5004. This 18" cable is made up of two insulated, AWG #8, copper conductors rated at 50 amperes. The hatch covering was modified to accept this penetrator and cable without weakening it structurally. Material was added to the original hatch increasing its thickness to allow a passageway to be drilled for the power cable. Extra metal was added beyond the point of contact with the sphere, to provide a mounting for the penetrator. Details of this installation are shown in Figures 6.2 and 6.3.

After the cells have been placed within the jar and interconnected, the 18" cable is run from the penetrator in the hatch to the cells. The hatch is then placed on the

sphere and secured by tightening down on the metal yoke provided. Some very thin non-metallic gasket material should be fitted between the straps of the yoke and the sphere to prevent scratching of the glass.

Once the hatch has been secured, this battery jar is in itself a fully contained energy storage system capable of supplying up to 3.24 KWH of electrical energy at a depth of 20,000 feet. Combined with other similar battery jars, a high energy density electrical storage system could be constructed that would save space and weight or provide more stored energy than a lead-acid type storage system. By using battery jars of Case I or Case II buoyancy condition in conjunction with an existing silver-zinc or lead-acid type storage system, the mission time, cruising speed and range, or the electrical payload capacity could be increased without major changes to the size of the craft. This "add-on" capability is the major advantage of this concept and is not available through the use of conventional storage subsystems.

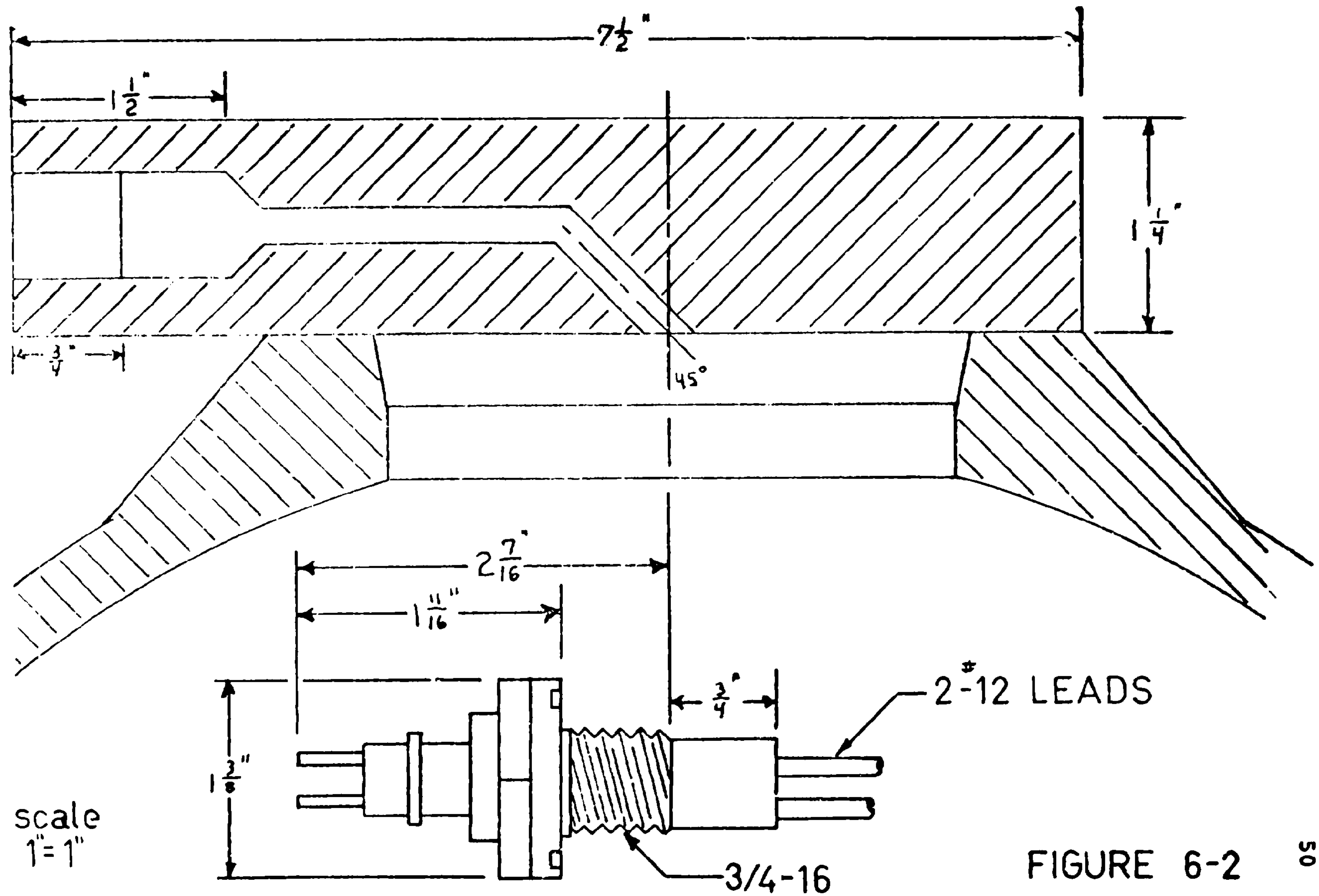
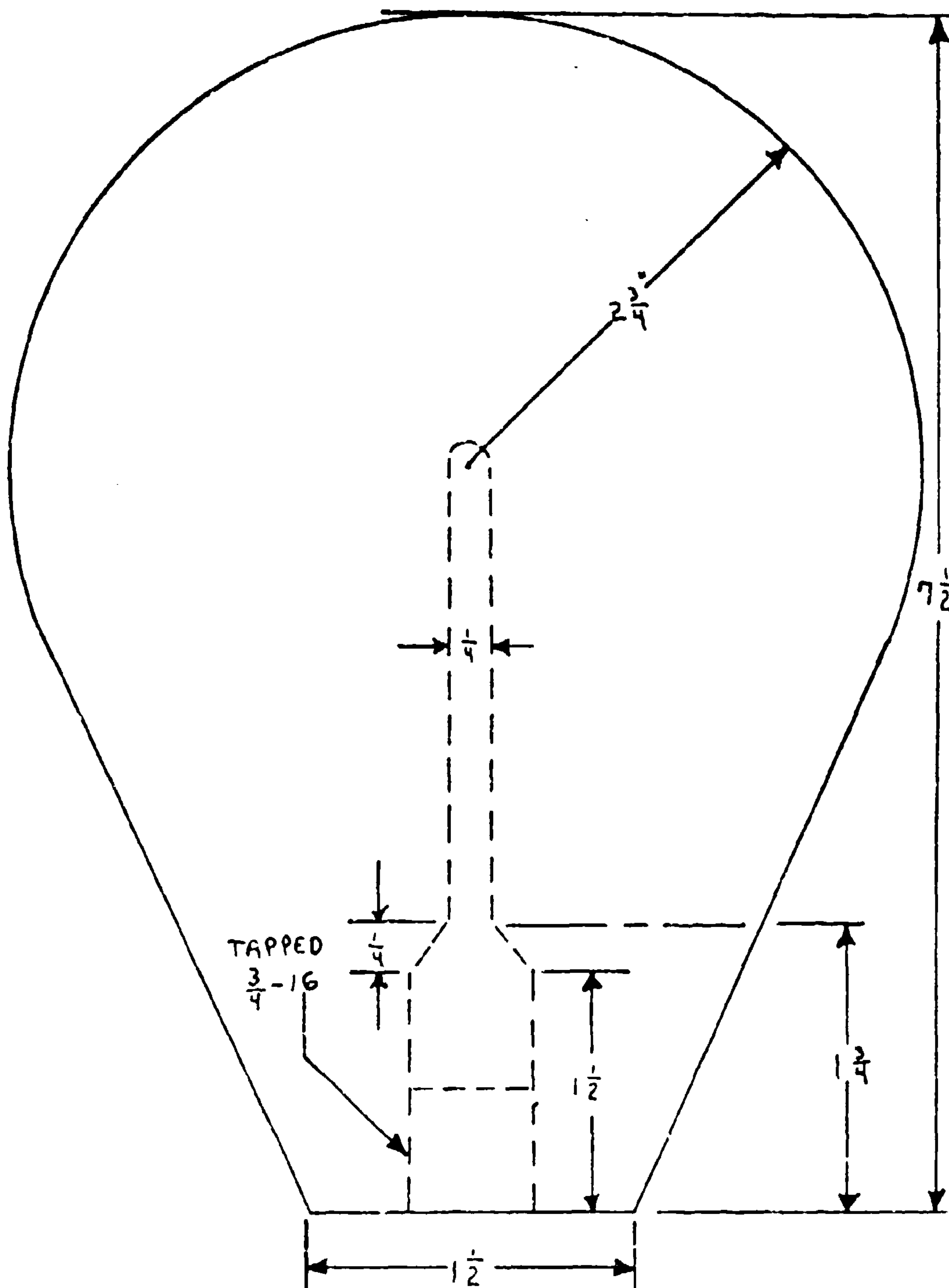


FIGURE 6-2

FIGURE 6-3 MODIFIED C-16 HATCH COVERING



CHAPTER VII

THE EXAMINATION AND EXPERIMENTAL DETERMINATION OF THE OPERATIONAL BEHAVIOR OF A SILVER-ZINC CELL DURING CHARGING, DISCHARGING, AND STAND FOR VARYING TEMPERATURES IN AN ENCLOSED ENVIRONMENT

Research concerned with the possible generation of gaseous products by a silver-zinc storage cell disclosed that hydrogen and oxygen gas could be evolved from such a cell during charge, discharge, and stand. (Reference 1). Since the design of the energy storage system presented here incorporate silver-zinc cells in sealed containers, the operational behavior of those cells had to be determined in order to compensate for any adverse characteristics.

When all available active materials have been consumed on charge, gassing occurs. Oxygen is evolved at the silver electrode and hydrogen at the zinc electrode. It is a common form of cell construction to include an excess of zinc-active material, resulting in oxygen being the only gas normally evolved on completion of charge and overcharge.

The silver-zinc cell is an extremely efficient electrochemical couple, almost all the stored energy is converted to electrical output and practically no gas should be generated on normal discharge. If one cell of a string is depleted before the other cells and is force discharged, hydrogen gas should evolve at the positive, silver electrode.

During charged stand, the negative electrode will self-discharge according to equation (7.1),

$$\text{eq(7.1)} \qquad Z_n + 2)H^- + 2H_2O \rightarrow Z_n(OH)_4^= + H_2 \uparrow$$

generating hydrogen. Lander and Snyder (Reference 15) observed that the gassing rate varied directly with the temperature.

In order to determine the exact amounts of gas to be expected during the charging and discharging cycles of the energy storage system, an experiment was conducted to simulate actual operating conditions. A Yardney Model LR-60 Silvercel$^{(R)}$ was obtained to serve as a test cell in this experiment. Figure 7.1 shows the test set up to measure the gaseous effluent of that cell. (An LR-60 was tested rather than an LR-58 when it was thought that the LR-60 would be the optimum cell for encapsulation. The results should provide insight in dealing with the gassing problem.) Various charge and discharge rates were used. The tests were run at room temperature and at a reduced temperature to simulate actual immersion in deep ocean waters.

The cell current was monitored regularly and adjustments made to the slide-wire resistor as needed. Charging current was held constant and terminated when the cell voltage rose to 2.0 volts. The discharge current was held constant and was terminated when 60 ampere-hours of energy was expended.

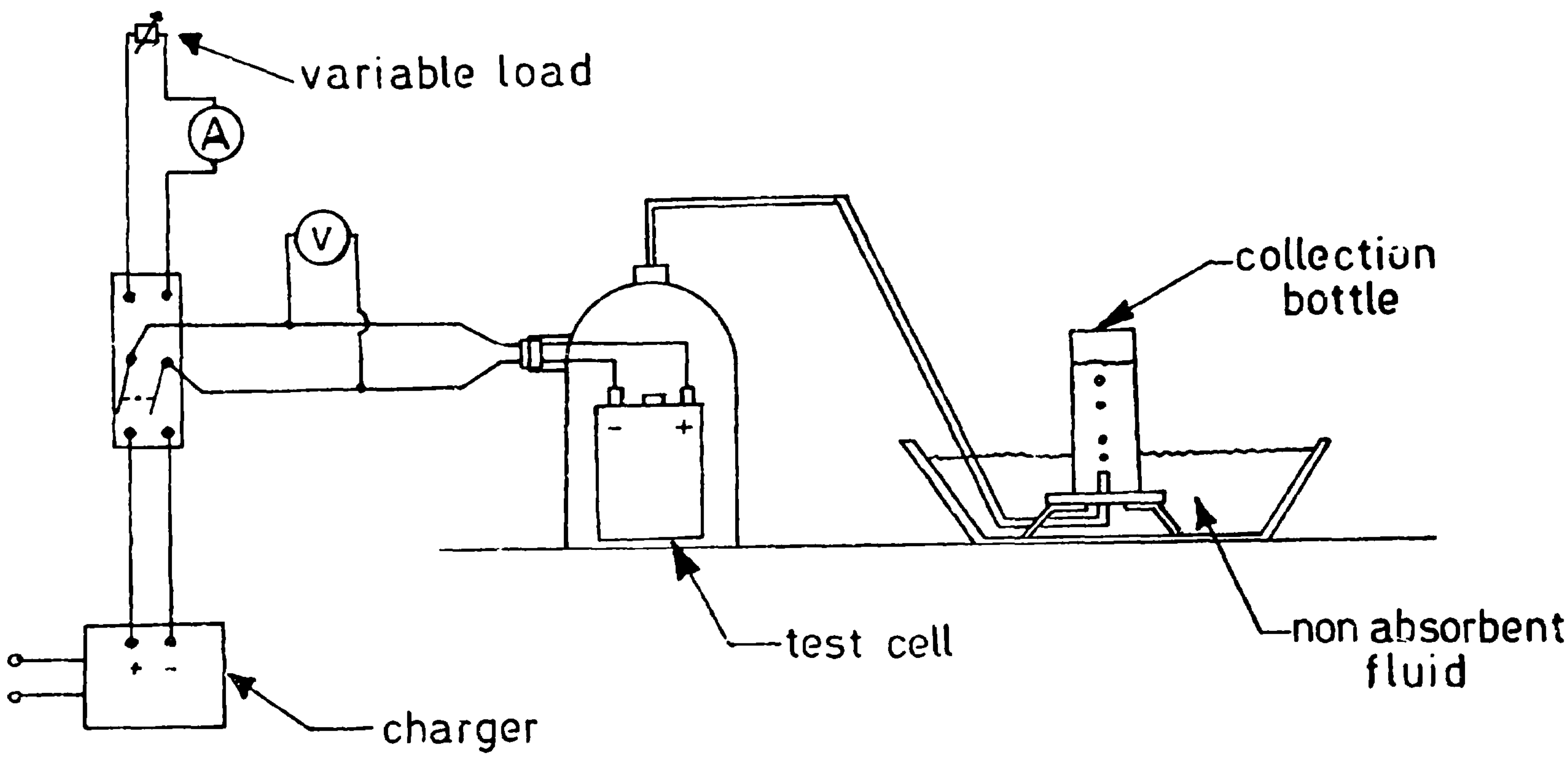


FIGURE 7-1 CHARGE/DISCHARGE TEST STATION

Table 7.1 shows the test cycle conditions and the quantity of gas collected during each stage.

To see what consequences this gas generation could have, the following calculations were made for a "worst case" condition: the twenty-four cell, Case III battery sphere.

Internal volume of C-16 sphere:	$1770\ \text{in.}^3 = 1.03\ \text{ft.}^3$
Cell volume (24 LR-58's):	$-\ 718\ \text{in.}^3$
	$1052\ \text{in.}^3$
Foam cell support (estimate):	$-\ 250\ \text{in.}^3$
Free air volume	$=\ 802\ \text{in.}^3$

the weight of this air is:

$$W_A = \left(\frac{0.07528\ \text{lbs.}}{\text{ft.}^3}\right)\left(\frac{1\ \text{ft.}^3}{1728\ \text{in.}^3}\right)(802\ \text{in.}^3)$$

$$\underline{W_A = 0.344\ \text{lbs.}}$$

If gas generation averages 20 cc for each period of charging, charged stand, and discharging for a total of 60 cc per cell, the twenty-four cells will produce a total of 1440 cc of gas during a charge-discharge cycle. Of this total, 960 cc should be hydrogen and 480 cc should be oxygen.

The weight of the oxygen generated will be:

$$W_{O_2} = \left(\frac{.08305\ \text{lbs.}}{\text{ft.}^3}\right)(480\ \text{cc})\left(\frac{1\ \text{ft.}^3}{28339\ \text{cc}}\right)$$

$$\underline{W_{O_2} = 0.0014\ \text{lbs.}}$$

Table 7.1 - Experimental Results, LR-60 Test

Test Cycle	Internal Temp. (°F)	Duration (Hrs.)	Average Gas Volume (cc)	Average Gassing Rate (cc/Hr)	
1.5 amp. charge	70-75	40	28.0	0.70	O_2
1.5 amp. charge	40-45	40	27.0	0.675	O_2
charged stand	70-75	24	15.8	0.66	H_2
charged stand	40-45	24	13.5	0.56	H_2
1.5 amp. discharge	70-75	40	32.0	0.80	H_2
1.5 amp discharge	40-45	40	30.0	0.75	H_2
3.0 amp. charge	70-75	20	18.5	0.925	O_2
3.0 amp. charge	40-45	20	18.0	0.90	O_2
charged stand	70-75	24	16.0	0.67	H_2
charged stand	40-45	24	13.5	0.56	H_2
3.0 amp. discharge	70-75	20	22.0	1.10	H_2
3.0 amp. discharge	40-45	20	22.0	1.10	H_2
6.0 amp. charge	70-75	10	38.0	3.80	O_2
6.0 amp. charge	40-45	10	35.0	3.50	O_2
charged stand	70-75	24	16.0	0.67	H_2
charged stand	40-45	24	13.6	0.56	H_2
6.0 amp. discharge	70-75	10	38.5	3.85	H_2
6.0 amp. discharge	40-45	10	35.0	3.5	H_2

The weight of the hydrogen generated will be:

$$W_{H_2} = \left(\frac{.00523 \text{ lbs.}}{\text{ft.}^3}\right) (960 \text{ cc}) \left(\frac{1 \text{ ft.}^3}{28339 \text{ cc}}\right)$$

$$\underline{W_{H_2} = 0.000178 \text{ lbs.}}$$

A mixture of air with 4-8% hydrogen will burn, and a mixture with more than 8% hydrogen will explode. A check was made to see if those conditions would exist with the Case III battery package. The partial pressure of the hydrogen was found and the percent of total volume determined.

The partial pressure of the hydrogen gas was found by use of the gas law:

$$PV = WRT$$

where, P - partial pressure of gas

V - volume available for expansion

W - weight of gas

R - gas constant

T - temperature, $^{\circ}$Rankine

The partial pressure of a gas is that pressure which it would exert if it alone occupied the entire volume, V, by itself at temperature T. For this case, involving hydrogen:

$$P_{H_2} = \frac{WRT}{V}$$

$$= \frac{(1.78 \times 10^{-4} \text{ lbs.})\left(766.8 \frac{\text{ft-lbs}}{\text{lbs.}^{\circ}\text{R}}\right)(530 \ ^{\circ}\text{R}}{(0.464 \text{ ft.}^3)}$$

$$P_{H_2} = 1.08 \text{ PSI}$$

that works out to 7.35% hydrogen concentration by volume, a highly burnable mixture. There does not seem to be any danger of the battery jars being damaged due to a pressure buildup, however, some means of eliminating the explosive potential of the system must be found.

Several methods could be employed to prevent the hydrogen concentration from reaching an explosive stage. Opening the battery jars after each discharge period, during or after each charging period, and following each period of stand would prevent a critical hydrogen buildup. Though perhaps the simplest method, venting each jar could prove to be too extensive an undertaking.

Injecting an inert gas into the battery jars in place of common air could prevent the formation of an explosive mixture. This procedure would have to be repeated whenever the hydrogen pressure buildup was released. This would prove costly and time consuming.

A third option would be the installation of a hydrogen eliminator. The active form of this device incorporates a heating element that oxidizes the hydrogen content to form steam. Silica gel or a similar type absorbent then picks up the resultant moisture. This method is very effective but would require some small expenditure of electrical energy and weight allowance. Perhaps some type of intermittent switching could be provided to activate a heating element briefly every few hours.

Inquiries to the Chemistry Department of the University of Massachusetts revealed the existence of a substance known as platinum black. This is a finely meshed or ground form of platinum that has a great affinity for hydrogen. It can absorb 10% of its own weight in hydrogen with no heating necessary. Once the platinum black has become saturated with hydrogen, heating it in the presence of oxygen drives off the hydrogen as steam.

One ounce of the element, weighing 0.0625 pounds, can therefore absorb 0.00625 pounds of hydrogen before it becomes saturated. For a Case III battery jar, that would provide protection against a hydrogen buildup for about thirty-five charge|stand|discharge cycles. A Case II battery jar would require hydrogen servicing after thirty-eight cycles, while a Case I jar could go through one hundred and five cycles before requiring service.

It is proposed that one ounce of platinum black be carried in each battery jar. The chemical, in a powdered form, should be held in a small, tray-like container near the top of the jar. The added weight of this type of hydrogen protection is negligible. The cost of one ounce of platinum black is $140. (Reference 26). A heating element could be provided that would operate only during charging conditions to reduce the required amount of platinum and the maintenance requirements.

CHAPTER VIII

INTEGRATION OF THE DESIGN CONCEPTS INTO WORKABLE ELECTRICAL SYSTEMS

As was mentioned earlier, each individual battery jar developed in Chapter IV could be operated as a complete, fully self-contained energy storage system. However, the low operating voltage and small amount of stored energy per jar would make that unfeasible if a DSV was to perform meaningful tasks while submerged. Many of these battery jars would need to be inter-connected to provide a substantial amount of stored energy at an acceptable voltage level.

The amount of stored energy required by a DSV would depend primarily upon the nature and duration of its mission. A high speed search type DSV with a long mission time would require far more stored electrical energy than a boat designed to spend only a few hours near the bottom while travelling at a slow speed. The ability of an individual craft to accommodate an energy storage system would also vary among the existing DSV's. The size of a boat determines the size and weight allowed for such a system.

In order to demonstrate ways of providing energy storage systems of various weights and sizes, the battery jars of each of the three cases of differing buoyancy will be incorporated into complete electrical storage systems.

These storage systems can feed either dc (direct current) or ac (alternating current) submersible motors for vehicle propulsion. Dc motors have been widely used because they can be operated directly from the battery supply, have good speed control characteristics, and overall efficiencies of about 70%.

The basic dc motor design requires a commutator and carbon brushes. These are very sensitive to any sea water intrusion, and the commutator bars may short. A dc motor is usually heavier than a comparable ac unit (Reference 11). The oil-filled dc motors require frequent maintenance for replacement of brushes. Alternating current induction motors are simpler in design and construction since they do not utilize brushes and commutators.

However, a dc to ac inverter is needed between the battery and an ac motor. Until recently these inverters were large, heavy, and inefficient, prohibiting their use aboard small submersibles. Solid-state inverters, newly developed, are showing great promise. The Westinghouse Deepstar 4000 uses ac motors operated from batteries through a solid state inverter. The propulsion system of the PX-15 research bathyscaphe uses inverter-fed three phase ac motors. At full speed, the inverter efficiency is reported to be nearly 95%.

It seems that further study is needed in this area to determine the optimum combination of power supply and motor design for highest efficiency at minimum weight. For this

paper, a dc "Alvin-type" propulsion system will be assumed. The storage capacity of these systems will range from 25 KWH (kilowatt-hours) to 500 KWH in the following steps: 25 KWH, 50 KWH, 75 KWH, 100 KWH, 150 KWH, 200 KWH, 300 KWH, 500 KWH.

So that the systems may have a common ground for comparison, the electrical loads will be standardized as follows:

Item	Operating Voltage	Power Required
1) main propulsion	96^{VDC}	9600 W (100^{A} for 10 HP)
2) lighting; 4, 500 W	48^{VDC}	500 W (10.4 Amp.) each
3) manipulator	48^{VDC}	2000 W (41.6^{A})
4) miscellaneous	48^{VDC}	2000 W (41.6^{A})

The total power required by these devices, operating at maximum rating, is 14.1 KW. Since these devices will not be operated at full ratings for the entire mission, a duty factor will be introduced for each. This factor will provide an adjustment to the power requirement of a particular load, by estimating what fraction of the maximum possible load will be required for what fraction of the entire mission. These adjusted power requirements are listed in Table 8.1.

Table 8.1 - Adjusted Power Requirements

Item	Duty Factor fraction of mission	fraction of power	Power Required	
1) Propulsion 9600 W,total	1/4	1 (full spd.)	2400 W	5.4 KW
	1/2	1/2 (normal cruise)	2400 W	
	1/4	1/4 (slow)	600 W	
2) Lighting	1/2	1 (all 4,500 W lights)	1000 W	
	1/2	1/2 (2,500 W lights)	500 W	
3) Manipulator	1/4	1	500 W	3.125 KW
	3/4	0		
4) Misc. (2000 W max.)	1/4	1	500 W	
	1/2	1/2	500 W	
	1/4	1/4	500 W	

The total adjusted power required is 8.525 KW. Multiplying this figure by mission time gives the required stored energy in kilowatt-hours. Dividing the amount of stored energy carried in a boat by that figure gives the mission duration in hours.

The individual battery jars for each case of differing buoyancy are summarized as follows:

Case I $\frac{W}{\Delta} = 0.656$

8 Yardney Model LR-58 Silvercels(R)

1.080 KWH capacity

12.0 V @ 9 amperes for 10-hour rate

Case II $\frac{W}{\Delta} = 1.0$

12 Yardney Model LR-90 Silvercels(R)

2.610 KWH capacity

6.0 V @ 43.3 amperes for 10-hour rate

Case III $\frac{W}{\Delta} = 1.08$

24 Yardney Model LR-58 Silvercels(R)

3.240 KWH capacity

12 V @ 27.0 amperes for 10-hour rate

Table 8.2 indicates the number of battery jars of each case that are required to store the desired amount of electrical energy. Also shown is the exact amount of energy stored and the mission duration for each case.

Table 8.2

desired stored energy (KWH)	25	50	75	100	150	200	300	500
number of Case I spheres required (1.08 KWH each)	24	48	72	96	144	192	288	480
amount of energy actually stored for Case I (KWH)	25.92	51.84	77.76	103.68	155.52	207.36	311.04	518.40
mission duration for Case I (Hrs.)	3.04	6.08	9.1	12.16	18.2	24.32	36.48	60.80
number of Case II spheres required (2.61 KWH each)	10	20	30	40	60	80	120	200
amount of energy actually stored for Case II (KWH)	26.1	52.2	78.30	104.4	156.6	208.8	313.2	522.0
mission duration for Case II (Hrs.)	3.06	6.12	9.2	12.24	18.36	24.48	36.72	61.2
number of Case III spheres required (3.24 KWH each)	8	16	24	32	48	64	96	160
amount of energy actually stored for Case III (KWH)	25.92	51.84	77.76	103.68	155.52	207.36	311.04	518.40
mission duration for Case III (Hrs.)	3.04	6.08	9.1	12.16	18.2	24.32	36.48	60.80

The battery jars of each of these storage systems could be connected to give various operating voltages and current levels. The determining factor in this decision is the equipment to be powered. The equipment that is commonly available is generally designed to be compatible with 12.0 V battery operation. That is, the equipment operates at 12.0, 24.0, 48.0, 60, or 120 volts. Propulsion motors may be run at various voltages, from 60 to 120 volts. The operating voltages for the sample loads were chosen for the sake of simplicity and with the understanding that a craft could operate with such a voltage supply. Each of these systems should provide two required voltages, 96 V and 48 V.

The manner in which the battery jars can be connected to provide operating voltages of 96.0 V and 48.0 V while insuring adequate energy for each bus will be discussed here for several of the storage amounts.

<u>System I, 25 KWH</u>

Case I - 24 battery jars [12.0 V, 1.08 KWH each]

3.04 hour mission

Required energy: 96 V bus - 16.4 KWH

48 V bus - 9.5 KWH

The required 96 V bus can be provided by connecting eight Case I battery jars together in series. Connecting two of these strings together in parallel will provide 17.28 KWH of stored energy.

The required 48 V bus can be provided by connecting four Case I battery jars together in series. Connecting two of these strings together in parallel will provide 8.64 KWH of stored energy.

It is evident that more energy is provided for the 96 V bus than required, while the energy provided to the 48 V bus is somewhat less than required. It is felt that the propulsion bus should be given a higher priority in an instance such as this when the bus requirements cannot be met exactly. Some curtailment of operations from the 48.0 V bus would be required.

Case II - 10 battery jars [6.0 V, 2.61 KWH each]

3.06 hour mission

Required energy: 96 V bus - 16.5 KWH

48 V bus - 9.6 KWH

The low operating voltage of the Case II jar makes it impossible to achieve the required 96.0 V for the propulsion bus. The use of a motor operating on a reduced voltage could be considered, but would introduce some difficulty in the comparison of the various system arrangements here.

Case III - 8 battery jars [12.0 V, 3.24 KWH each]

3.04 hour mission

Required energy: 96 V bus - 16.4 KWH

48 V bus - 9.5 KWH

By wiring all eight battery jars in series, the required 96 V can be obtained for the propulsion bus. That arrangement does not leave any battery jars to be used for the 48.0 V bus. To provide this 48.0 volts, a tap will be made between the fourth and fifth jars. During the first half of the mission, the cells in these lower four jars will be discharged at a higher rate than those cells in the upper four jars. In order to prevent a forced discharge of the cells in the lower four jars, relay circuits will be used to switch the 48.0 V tap to the top four battery jars. A close watch will be needed in order that the tap switching takes place at the midpoint of the mission.

System II, 50 KWH

Case I - 48 battery jars [12.0 V, 1.08 KWH each]

6.08 hour mission

Required energy: 96 V bus - 32.8 KWH

48 V bus - 19.0 KWH

The required 96 V bus can be obtained by wiring eight of these Case I battery spheres together in series. Connecting four of these strings together in parallel will provide 35.56 KWH of stored energy. Connecting four of the Case I battery jars in series results in a bus voltage of 48.0 volts. By connecting four of these strings in parallel 17.28 KWH of stored electrical energy is available to this bus. Again, for this system, the energy available for the

propulsion bus is slightly more than what was actually required, while the energy supplied to the 48.0 volt bus was slightly less than what was estimated.

Case II - 20 battery jars [6.0 V, 2.61 KWH each]

6.14 hour mission

Required energy: 96 V bus - 33.0 KWH

48.0 bus - 18.2 KWH

The required 48 V bus can be achieved by connecting eight Case II battery jars in series. These battery jars will provide 20.88 KWH of stored energy for that bus. The remaining twelve battery jars can only supply 72.0 volts when they are all connected in series. This arrangement provides 31.32 KWH of stored energy for the propulsion bus. The energy available to the 48.0 V bus is slightly greater than that required, while that available for the propulsion bus is slightly less than required. The Lear Seigler propulsion motor is capable of operation at a reduced voltage of 72.0 volts, however, some curtailment of activity would be necessary.

Case III - 16 battery jars [12.0 V, 3.24 KWH each]

6.08 hour mission

Required energy: 96 V bus - 32.8 KWH

48 V bus - 19.0 KWH

The 96.0 volts required for the propulsion bus can be obtained by wiring eight Case III battery jars in series.

This string is able to provide only 25.92 KWH of stored energy. Unless a severe reduction in propulsion usuage is made, additional energy must be supplied. This can be done at a 96.0 V level only by connecting another string of eight cells in parallel with the first. Again, no jars are left to be used for the 48.0 V bus, necessitating the use of a switched tap as before.

System IV, 100 KWH

Case I - 96 battery jars [12.0 V, 1.08 KWH each]

12.16 hour mission

Required energy: 96 V bus - 65.6 KWH

48 V bus - 38.0 KWH

The required 96.0 V for the propulsion bus can be obtained by wiring eight Case I battery jars in series. Connecting eight of these strings in parallel will provide 71.12 KWH of stored energy. Wiring four Case I battery jars in series will provide the necessary voltage for the 48.0 V bus. Connecting eight of these strings in parallel provides 34.56 KWH of stored energy.

Case II - 40 battery jars [6.0 V, 2.61 KWH each]

12.28 hour mission

Required energy: 96.0 V bus - 66.0 KWH

48.0 V bus - 36.4 KWH

The required 48.0 V can be obtained by wiring eight Case II battery jars in series. Connecting two strings of these provides 41.76 KWH of stored energy. The propulsion bus is again limited to 72.0 V for this Case II type system. The 72.0 V is obtained by wiring twelve Case II battery jars in series. Two strings such as these in parallel provide 62.64 KWH of energy available for propulsion.

Case III - 32 battery jars [12.0 V, 3.24 KWH each]

12.16 hour mission

Required energy: 96 V bus - 65.6 KWH

48 V bus - 38.0 KWH

The energy required for the 96.0 V bus requires the use of all the available battery jars. The jars are to be arranged in four paralleled strings of eight jars each. A switchable tap is to be used to provide power for the 48.0 V bus.

These nine systems were developed as examples of what could be accomplished with the three different cases of battery jars. It is evident from these simple examples that, for an extended mission time or an increase in the storage capacity of a boat, battery jars need be added in parallel to those already employed. It must be realized, however, that battery additions should be made in groups no smaller than the number needed to achieve a particular bus operating voltage. For instance, with a bus voltage of 48.0 volts,

only strings of four 12.0 V battery jars should be added.

It is very difficult to propose a design for the energy storage system of a DSV without knowing exactly what mission is to be undertaken by that boat. The estimated loads for the previous examples would fit a moderately active, exploratory type DSV, and are used to assist in the determination of required energy needs for each bus.

Once the amount of required stored energy has been determined, and a decision made upon which case battery jar is to be used, the number of battery jars needed, is fixed. In order to simplify the power distribution system, all the equipment selected for a particular craft should be capable of operation at the same voltage level. Much of the available equipment needed for such a boat is designed to operate at low voltages, often multiples of 12.0 volts, to be compatible with lead-acid automotive type batteries. Propulsion motors are generally operated at a higher voltage to keep the current flow as small as possible. In most instances, two separate busses are desirable, and sometimes three. The reasoning behind multiple bussing is that in the event of power failure to a critical system, rewiring could be accomplished to enable the craft to operate to some extent. A battery failure on a craft using only one power distribution bus could prove disastrous.

A further example of an electrical storage system design is the following. It is assumed that a DSV to be built

requires an energy storage system capable of storing 75 KWH of electrical energy using Case I spheres. It is further required that 50 KWH be reserved for propulsion, leaving 25 KWH for lighting, manipulators, communications, and other miscellaneous needs. Table 8.2 indicates that 72 Case I battery jars are required for this system, forty-eight to be used for propulsion and twenty-four to be used for the remaining electrical loads.

The propulsion system for this boat will consist of one main drive motor and two smaller side drive motors. A 108.0 volt bus will be provided for the main drive motor and a 72.0 volt bus will be provided for each of the two side drive motors.

For the 108.0 volt bus, nine Case I battery jars will be connected in series. Four of these strings in parallel provide a storage capability of 38.88 KWH. With a mission time of eight hours, 45 amperes can be drawn continuously from this source. This is sufficient to drive a 5 H.P. motor. A two conductor underwater cable of size AWG #2 should be run from the junction box to the motor. Each battery jar can supply 11.25 amperes to the junction box. The cable connecting the battery jar to the junction box should be a two conductor underwater cable of size AWG #12.

The votage required for the 72.0 volt propulsion bus is obtained by wiring six Case I battery jars in series. Two of these strings in parallel provide 12.96 KWH for the

side propulsors. Each motor can be supplied w[illegible] .5 amperes for four hours. The motors can develop 1.5 H.P. each under these conditions. An underwater cable with two conductors, each size AWG #8, should be used between each side motor and the junction box. Each of these battery jars supply 11.25 amperes to the junction box. The cables connecting the battery jars to the junction box should be a two conductor underwater cable of size AWG #12.

The voltage for the 48.0 volt bus is obtained by connecting four Case I battery jars in series. Six of these strings wired in parallel provide 25.92 KWH of stored energy. A current of 67.5 amperes can be drawn from this source for an eight hour mission. This source is to supply power to many different devices, making it hard to specify what size cable should be used for each item. The battery jars themselves can deliver up to 11.25 amperes to the junction box. The cable connecting a battery jar to the junction box should be a two conductor underwater cable of size AWG #12.

The junction box that has been mentioned several times in the description of this energy storage system is used to tie the individual battery jars together into the desired configurations, and to connect each battery jar to a charger after each mission. This junction box can be mounted either within the personnel sphere or in a free-flooding area. If mounted within the pressure hull, the junction box can be a simple patch panel with [illegible] cables, or a sealed package

containing numerous electromagnetic relays. If mounted in a free-flooding area, the junction box must use relays protected by a pressure-proof container or encased in a pressure compensated compartment.

The main advantage of having the junction box inside the pressure hull is the safety feature inherent in the easy access to the power cables. Repairs to such malfunctions as blown fuses or faulty relays could be handled quickly by the crew without the need for surfacing. If a battery jar became flooded, or otherwise affected the output of a series string of jars, it could be quickly checked and isolated. If a change in power requirements became necessary while the craft was submerged, the reconnecting of the battery jars could be easily accomplished.

The major disadvantage of this type of arrangement is that a large two conductor cable must be brought through the hull for every battery jar in the energy storage system. The system under consideration here would require seventy-two pressure hull penetrations. Not only are these fittings heavy and expensive, but each penetration of the pressure hull increases the chance for a serious failure and subsequent leakage of a fitting.

Mounting the control box in a free-flooding area introduces the problem of keeping the salt water away from the numerous relays and fuses. This circuitry may be protected in either of two ways: (1) relays and assorted components

enclosed in pressure-proof vessels, or (2) switching circuits immersed in a compatible fluid, pressure compensated.

The pressure-proof system is possible; however, the numerous cable penetration again increases the possibility of a serious leakage problem. It is very important that this portion of the energy storage system be protected against failure of any sort.

Recent studies by the U. S. Navy concerning the behavior of relays, fuses, and electrical insulation immersed in various fluids has shown the feasibility of such an arrangement. (References 4, 10, 18, 19.) A pressure compensated junction box should not have the sea water leakage problems of a pressure-proof system since there is no pressure differential across the walls of the box. The pressure forces due to operating depth are transmitted by a flexible membrane, through a non-conducting fluid, and hence to the inside walls of the container. It is this type of control box that will be proposed in this design.

The previous example shows how a simple design for an energy storage system progresses, from the knowledge of the energy requirement of a boat. The process can be repeated for any system, using any of the three different cases of battery jars.

CHAPTER IX

ESTABLISHMENT OF OPERATIONAL CONSIDERATIONS AND GUIDELINES FOR A A_gZ_n ENERGY STORAGE SYSTEM

The operational considerations and guidelines for a silver-zinc storage system presented here are based upon the 75 KWH system developed in the preceding chapter, but are applicable to other similar systems.

When first obtained from the manufacturer, the storage cells are in a discharged condition. Throughout the construction of a boat and installation of the energy storage system, the cells should remain uncharged. This is to prevent their self-discharging with subsequent gassing and loss of energy.

Although the Silvercels(R) can be operated in any position, for optimum service, upright is recommended. The filler and vent plug is supposedly leakproof and spillproof, however, in this concept the cells are mounted and secured in an upright position within the glass spheres to prevent any loss of electrolyte. These loaded spheres should be handled and installed so that the cells remain in this upright position.

Prior to the deployment of the craft, the cells of the storage system should be brought up to full charge. The optimum arrangement for charging the storage cells would be to charge each cell individually, monitoring the cell voltage

to determine the end-of-charge condition. This charge completion is indicated by a sharp rise in cell voltage to 20 volts.

Charging the cells of a battery jar individually, however, would require that two wires be brought out of a jar for each cell. Bringing out only the positive leads and a common ground would either require an internal relay or will prevent the cells from being connected in series, later. Either of these methods results in a prohibitively complex charging system.

The charging of the A_gZ_n cells should be accomplished by the use of a modified constant potential type charger consisting of a voltage regulator and current limiter in series with each individual battery jar.

Variation of electrical characteristics among the cells could result in varying depths of discharge, in terms of rated capacity, for individual cells. If a number of these cells were charged in a series string, with each receiving an equal amount of energy, some might not reach a full charge level, while others might be overcharged. Being undercharged would not physically damage a cell, but would result in a reduced capability during the following mission. Overcharging of a cell could be damaging and would result in the generation of gaseous effluents. Both of these situations are to be avoided if possible. Keeping the number of cells to be charged together at a minimum is perhaps the simplest

way to avoid this occurrence of uneven charging.

The eight cells in the battery jars of the system under consideration can be charged together without much danger of uneven charge distribution, but the jars should be charged and monitored individually.

Charging requirements for a single LR-58 Silvercel(R) are (1) charging voltage of 1.75 volts, (2) charging current of 4.0 amperes (Reference 27). For eight cells in series, a charger providing 14.00 volts at 4.0 amperes is required. The jar voltage must be monitored and provision made for disconnecting the charger when that voltage has reached 16.00 volts. This could be done with a human operator or by complex electronic voltage sensing circuitry. After the cells in the battery jars have been fully charged, and if their use is not anticipated for a long period of time, charging should be terminated and the system returned to charge a few hours prior to its expected use. Whenever long periods of idleness are expected between missions, the cells should be left in a discharged state until just before the next mission.

The underwater activities of a boat should generally be planned well in advance of a particular mission. Care should be taken to insure that the tasks required are well within the operational capability of the energy storage system, leaving a certain amount of unused energy as a safety precaution. An estimated power profile should be drawn up so

that the condition of the energy storage system could be known to the operators at any point during that mission. A typical power profile based on the 75 KWH system developed in the preceding chapter is presented here as a guide. The energy available to each bus is shown in Table 9.1, and the manner in which it is to be consumed is demonstrated. Fitting this energy allowance to the proposed eight-hour mission results in the energy timetable or power profile shown in Figure 9.1.

The power profile of Figure 9.1 is an estimation of how the 75 KWH of stored energy is to be expended on the proposed mission, and is broken down as follows:

0.0-1.0 hours:	main and secondary propulsion on full; lights and cameras running.
1.0-2.0 hours:	main and secondary propulsion at normal; lights and cameras running.
2.0-3.0 hours:	main propulsion at normal, secondary off; lights and cameras running.
3.0-3.5 hours:	main propulsion reduced to slow, secondary off; lights and cameras on, manipulator activated.
3.5-4.5 hours:	main propulsion on slow; secondary on slow; lights and cameras on; manipulator in use.
4.5-5.0 hours:	main propulsion on slow; secondary off; lights and cameras on, manipulator in use.
5.0-6.0 hours:	main propulsion at normal cruise; lights and cameras on.
6.0-7.0 hours:	main propulsion to full power; lights and cameras on.
7.0-8.0 hours:	main propulsion reduced to normal; secondary on to normal speed; lights and cameras on.

Table 9.1 - Energy Allocation, 8 Hour Mission, 75 KWH

1) 108 V bus; 38.88 KWH available; main propulsion

Item		Operating conditions; 8 hours total		
17 H.P. motor	- full speed;	2 hours - (108 V) (80 A) = 8.64 KW or	17.28 KWH	(9 H.P.)
	- normal cruise;	4 hours - (108 V) (45 A) = 4.86 KW or	19.44 KWH	(4.5 H.P.)
	- slow speed;	2 hours - (108 V) (10 A) = 1.08 KW or	2.16 KWH	(1.0 H.P.)
			38.83 KWH	

2) 72 V bus; 12.96 KWH available; secondary propulsion

Item		Operating conditions; 4 hours total		
one of two 5 H.P. motors	- full speed;	1 hour - (72 V) (30 A) = 2.16 KW or	2.16 KWH	(2 H.P.)
	- normal cruise;	2 hours - (72 V) (22.5 A) = 1.62 KW or	3.24 KWH	(1.5 H.P.)
	- slow speed;	1 hour - (72 V) (10 A) = 0.72 KW or	0.72 KWH	(.75 H.P.)
			6.12 KWH	(1 motor)

Total energy reserve of 0.72 KWH

3) 48 V bus; 25.92 KWH available; auxiliary & payloads

Item	Operating conditions	
lighting	- 2000 watts for 8 hours -	16 KWH
manipulator	- 2000 watts for 2 hours -	4 KWH
cameras	- 250 watts for 8 hours -	2 KWH
comm. & internal	- 250 watts for 8 hours -	2 KWH
		24 KWH

Total reserve of 1.92 KWH (for pumps, ballast, and trim)

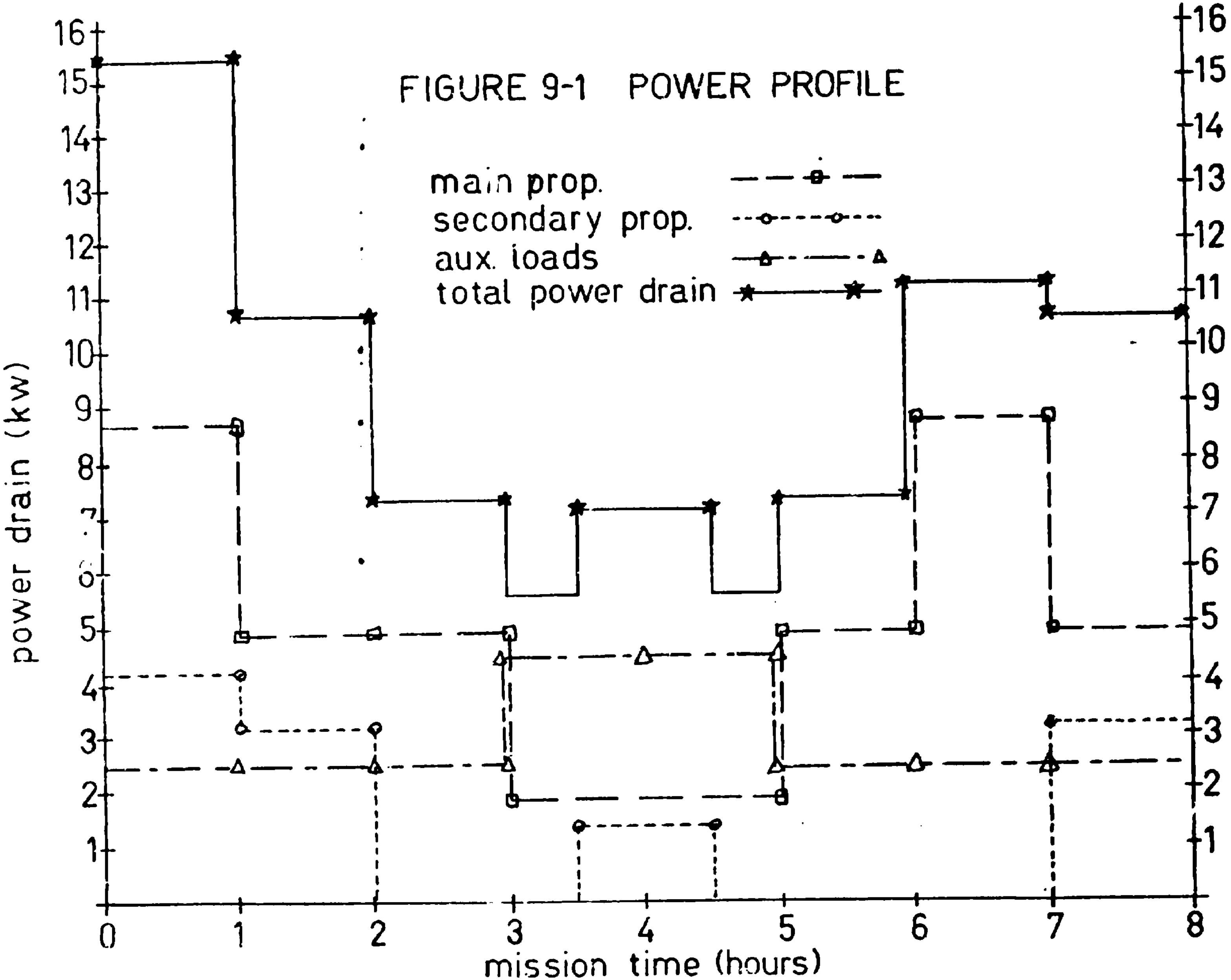


FIGURE 9-1 POWER PROFILE

By keeping track of the actual power drains during a mission and entering them on a plot such as Figure 9.1, a DSV operator could estimate the power consumption of the craft with high accuracy. In the event of deviation from the pre-mission plan, an operator could determine what amount of stored energy was left, and what changes would have to be made to use the remaining energy to best advantage.

CHAPTER X

MECHANICAL ARRANGEMENTS AND HANDLING CRITERIA FOR THE INDIVIDUAL BATTERY JARS OF THE ENERGY STORAGE SYSTEM

To use the battery packages developed in the previous chapters, some mechanical means of securing the spheres to a DSV must be devised. In this chapter, such a holding mechanism will be proposed, and its installation on a small DSV shown.

An encapsulated storage cell system external to the pressure hull and embedded in some manner throughout the floatation material of the hull necessitates a type of construction which will allow access to much of the vehicle while at sea. Any work done on the energy storage system while at sea would allow exposure of nearly all hull components to sea air and sea spray while in the dismantled condition. When the craft submerges, these components would be in direct contact with the sea water. In order to reduce corrosion effects and eliminate the possibility of establishing a dielectric cell, the components of the sphere handling system will be constructed of glass reinforced plastics (GRP).

To hold the battery spheres securely, cylinders will be formed of thin sheets of GRP. These thin sheaths will be slightly larger in diameter than the outside dimensions of the clamping tabs on the yoke used to hold the entry hatch,

to accommodate several spheres stacked vertically. The battery spheres will be held in place by pre-cast, 36 PCF foam cradles. The 36 PCF foam will offset the added weight of the GRP and power cables since this arrangement is free-flooding. The packed cylinders will then slide vertically into slightly larger ones that are mounted rigidly to a skeletal framework. Figure 10.1 shows the details of the packed cylinder concept.

The packed cylinder will be fitted with small ribs running vertically along the length of its outside surface. These will provide spacing and guidance between the inner cylinder and the firmly fixed outer cylinder. The outer cylinder will have corresponding grooves to accept the positioning ribs.

To show that this packing arrangement does satisfy the Case I buoyancy condition of $W/\Delta = 0.656$, Table 10.1 gives the weights of the various components of the system shown in Figure 10.1.

Table 10.1 - Weights of Components of Packed Cylinder Arrangement

Item	Weight	Displacement
3 Case I spheres	165	251.5
36 PCF foam cradles	140	257.3
GRP cylinders	41	19.
Totals	346	527.8

$$\frac{\text{weight}}{\text{displacement}} = 0.656$$

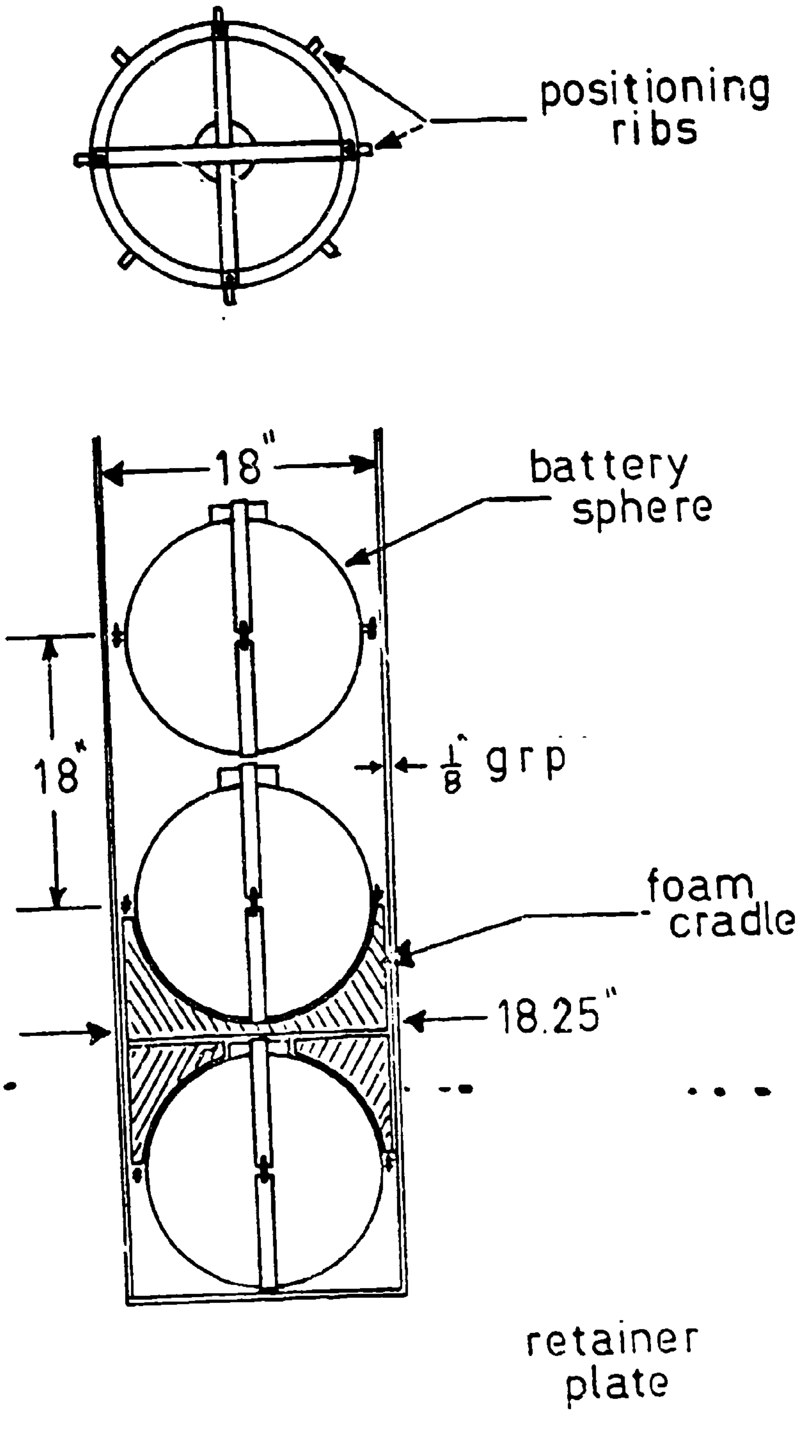


FIGURE 10-1 PACKED CYLINDER CONCEPT

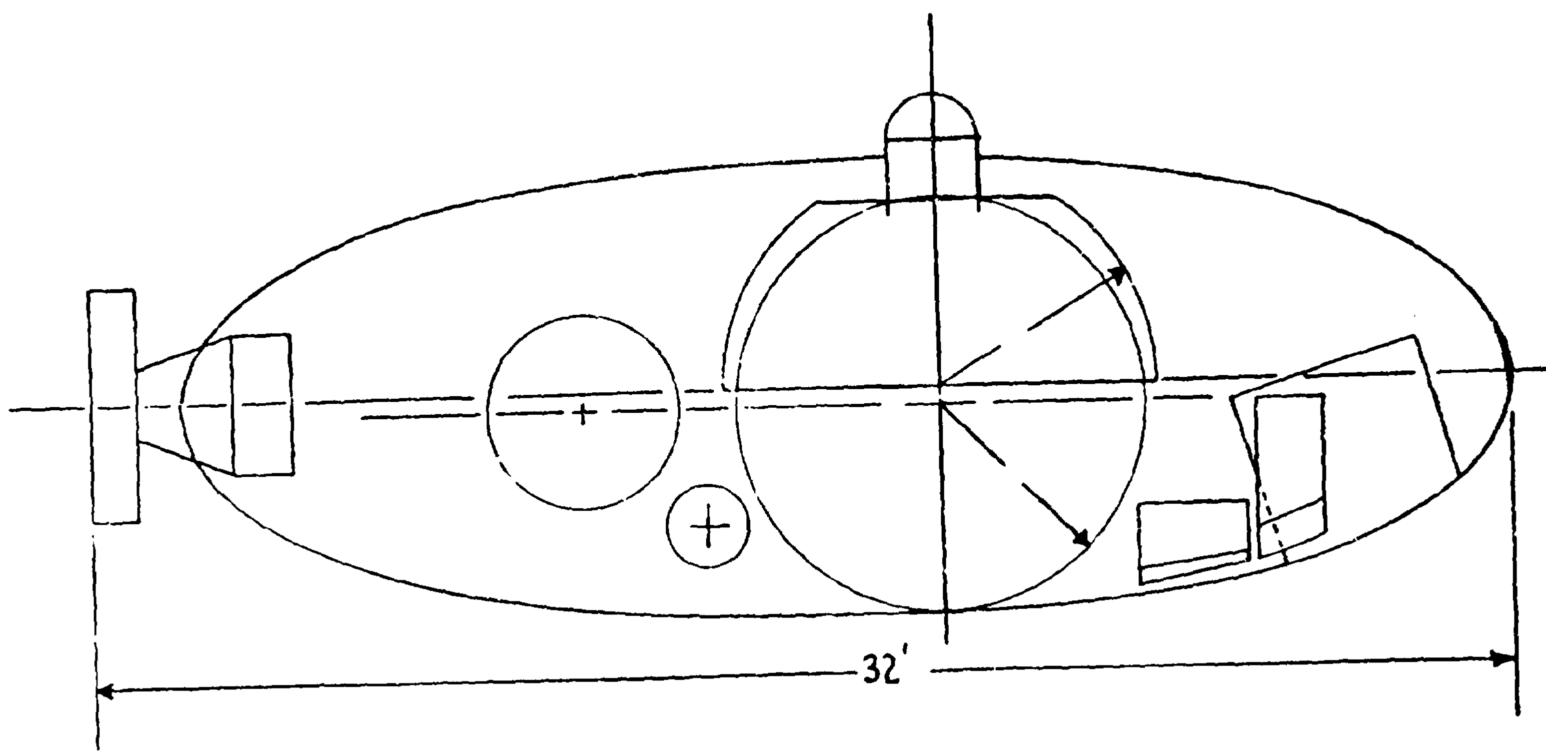
To determine how much electrical energy could be stored aboard a DSV in this manner, a boat developed by Kattavola (Reference 28) for Navy Project #6 (ONR-N00014-68-A-0146-6) will be fitted with this storage system. This boat is the first in a family of HY-100 steel, four-man boats. Its length overall is thirty-two feet. Two other boats, forty feet and fifty feet in length, make up the family. The balanced, thirty-two foot boat is shown in Figure 10.2. The volume not occupied by the personnel sphere, ballast system, or propulsion package is 42 PCF floatation material. The voids at the bow of the boat are for mounting of payload devices.

Figure 10.3 shows the top view of this craft. The section lines serve to divide the boat into equal segments, and indicate the center line of the packed cylinder locations. Figures 10.4 through 10.14 show the number of battery jars that can be fitted into cylinders in each of the segments so as not to disturb the present hull outline. It appears that ninety Corning 16" OD glass spheres can be stored in that thirty-foot DSV.

The Case I battery spheres (W/A = 0.656) have a storage capacity of 1.08 KWH each. These ninety spheres therefore provide an energy storage system with a total capacity of 97.20 KWH.

Each of the ninety spheres would need to be serviced periodically. Possibly more energy could be stored or less

FIGURE 10-2 A BALANCED THIRTY TWO FOOT DSV



scale 1″ = 4′

FIGURE 10-3 CENTERLINES OF CIRCULAR HULL SECTIONS THAT HOUSE THE BATTERY CYLINDERS

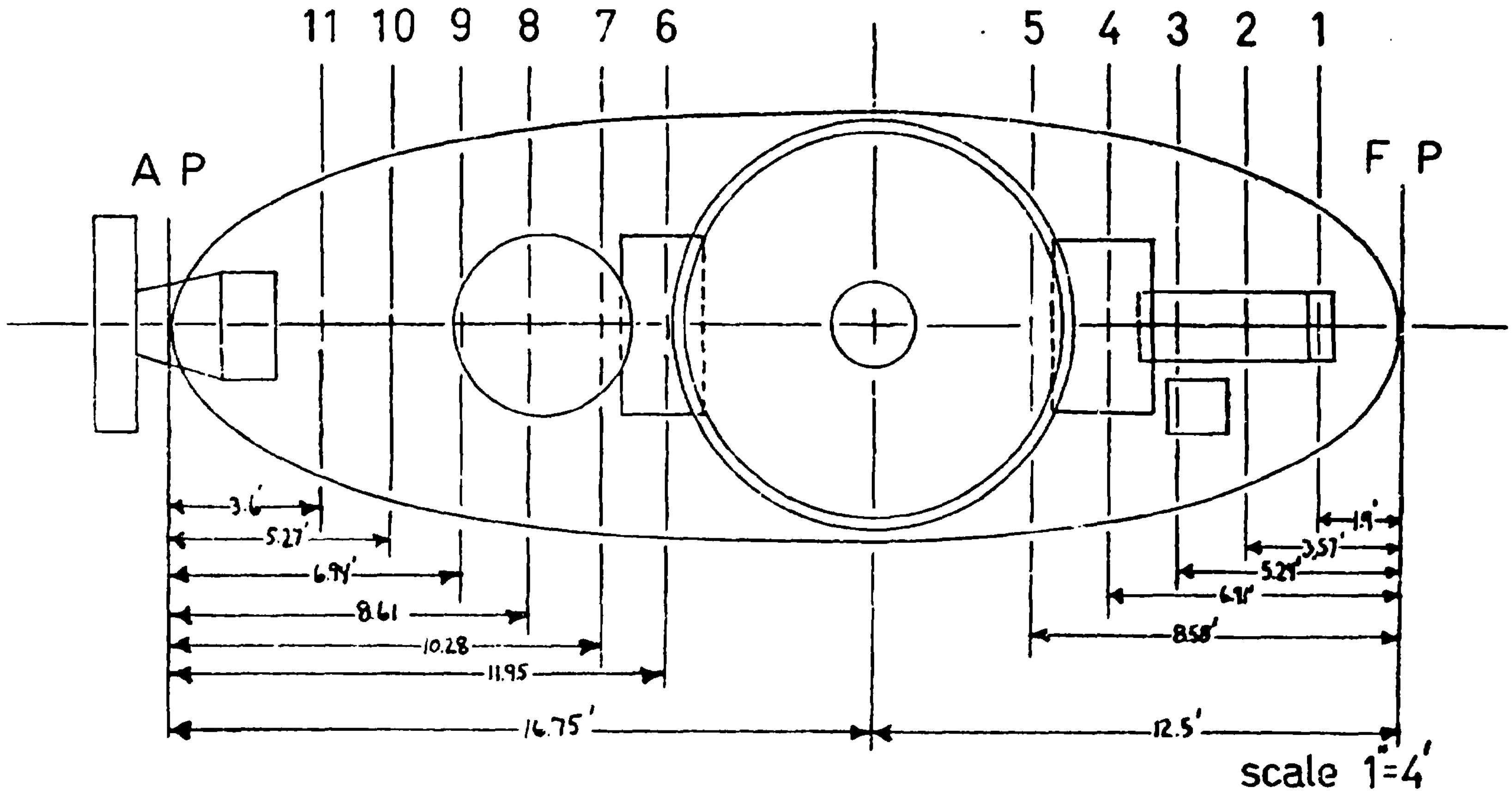
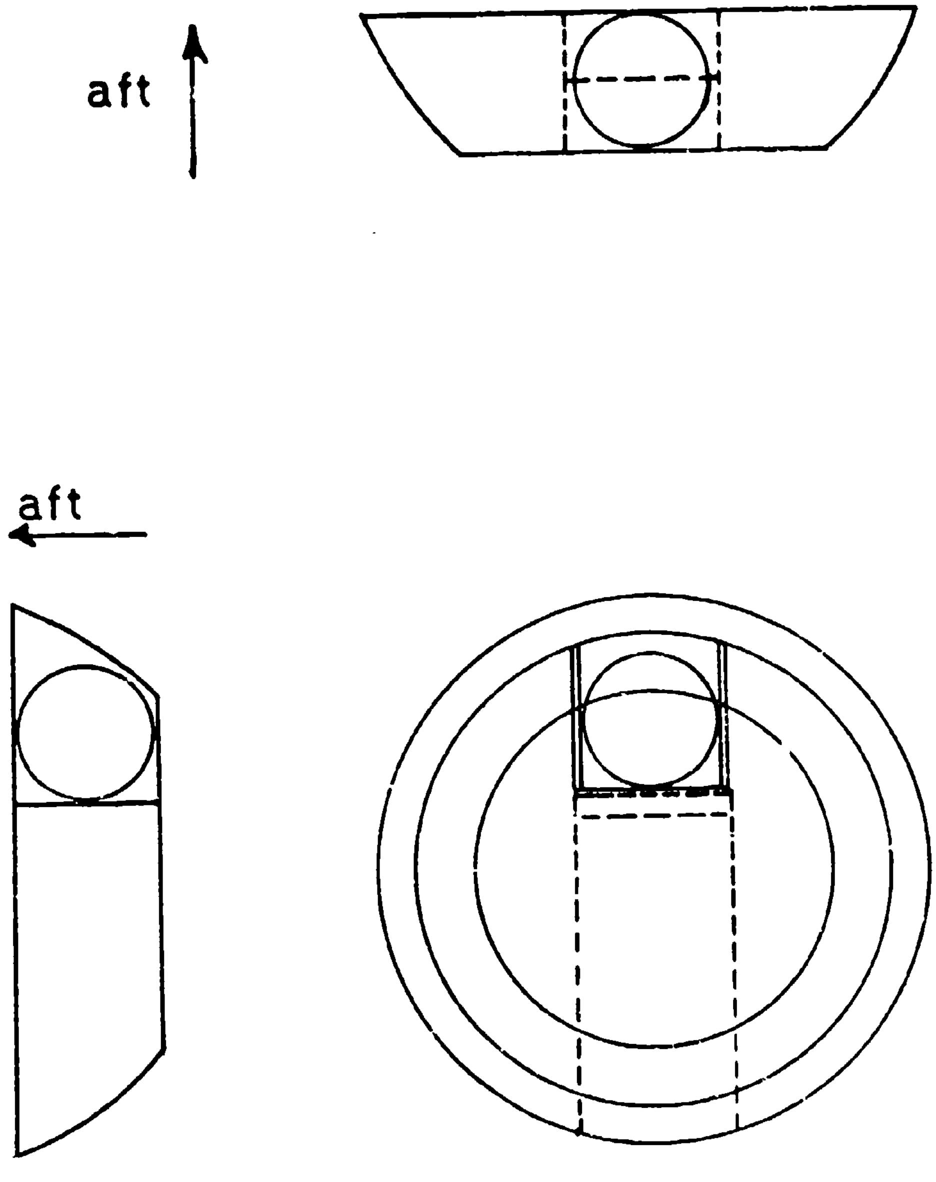
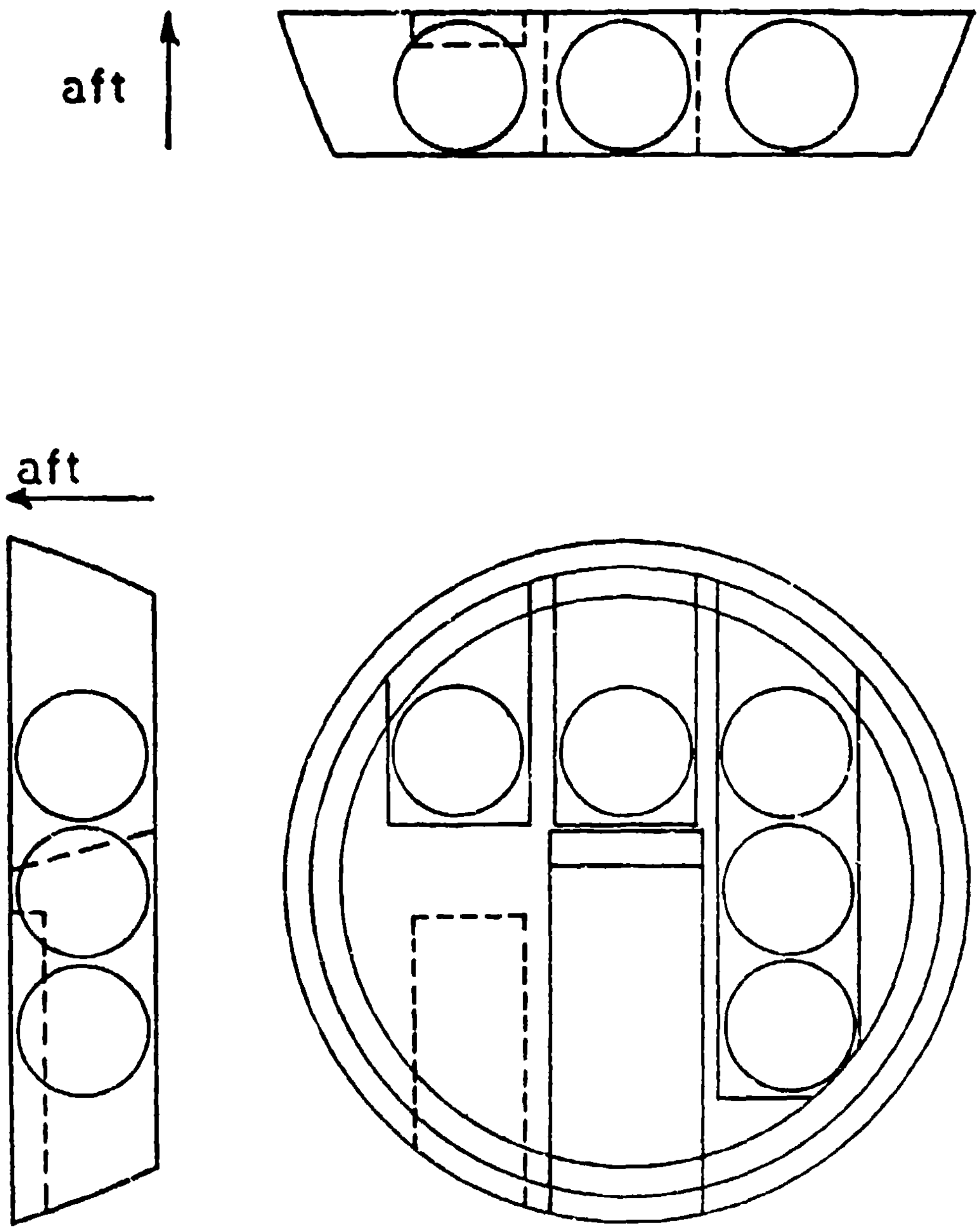


FIGURE 10-4 SECTION 1, 1.9′ AFT FP



scale 1″= 2′

FIGURE 10-5 SECTION 2, 3.57′ AFT FP



scale 1"=2'

FIGURE 10-6 SECTION 3, 5.24' AFT FP

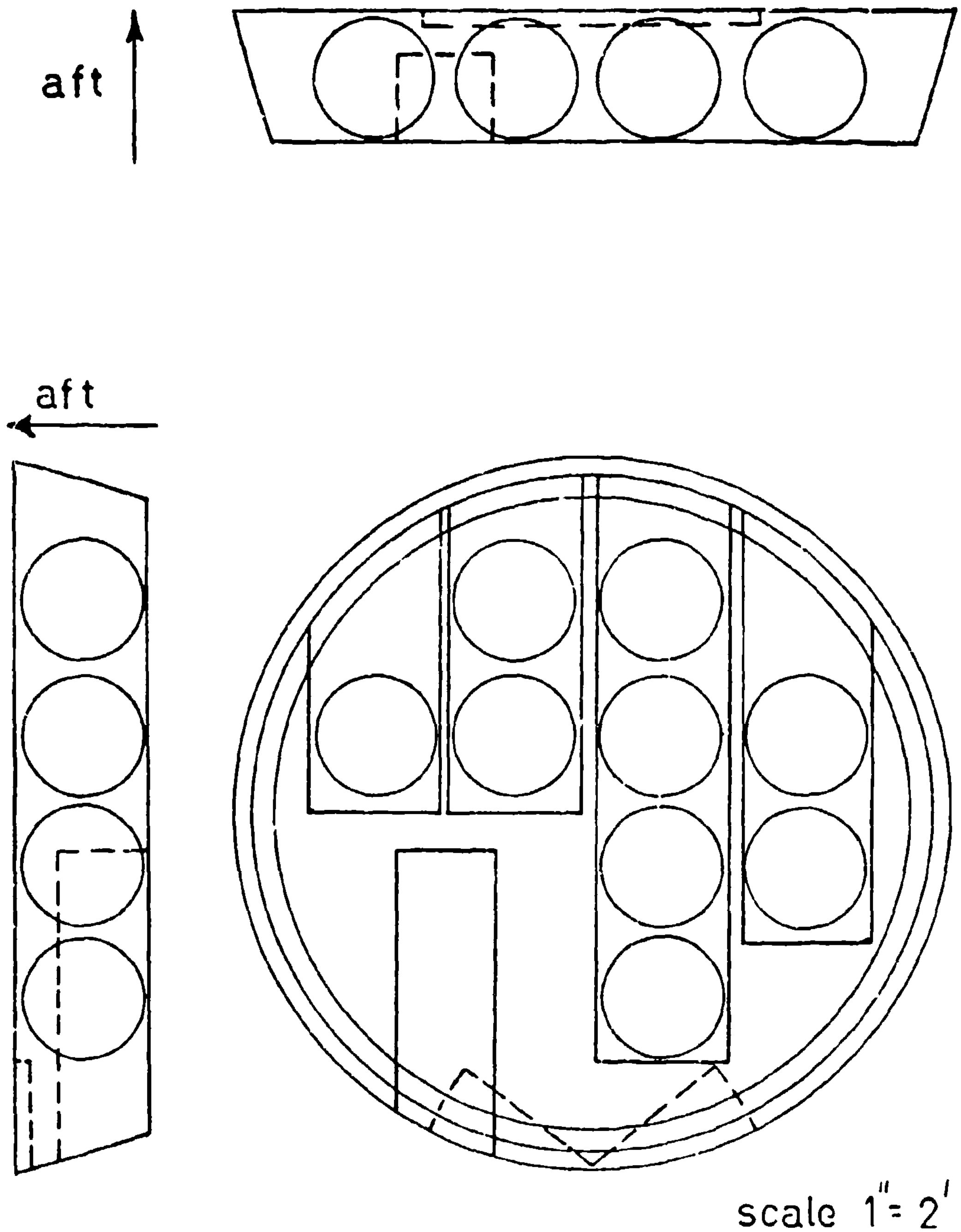


FIGURE 10-7 SECTION 4, 6.91′ AFT FP

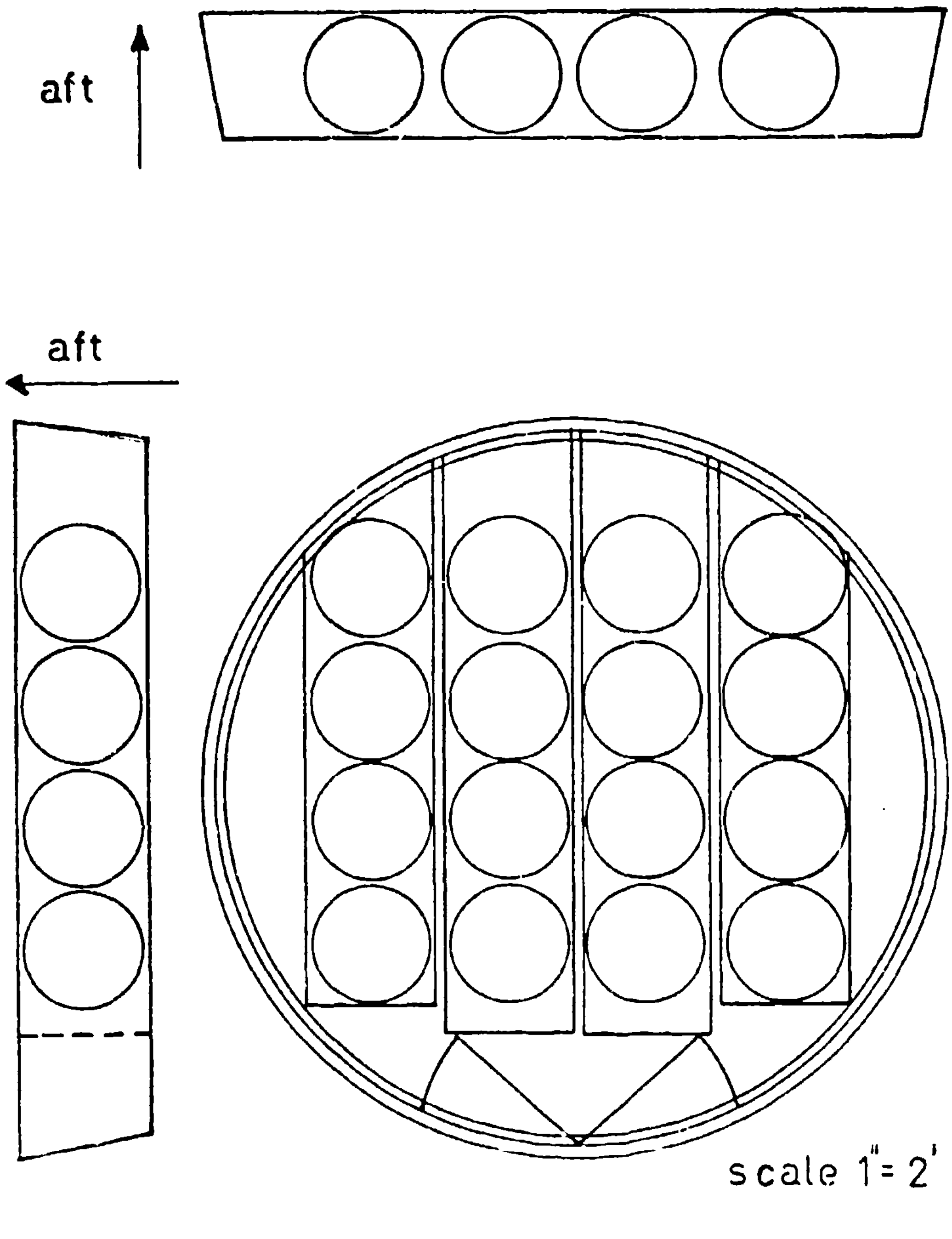


FIGURE 10-8 SECTION 5, 8.58′ AFT FP

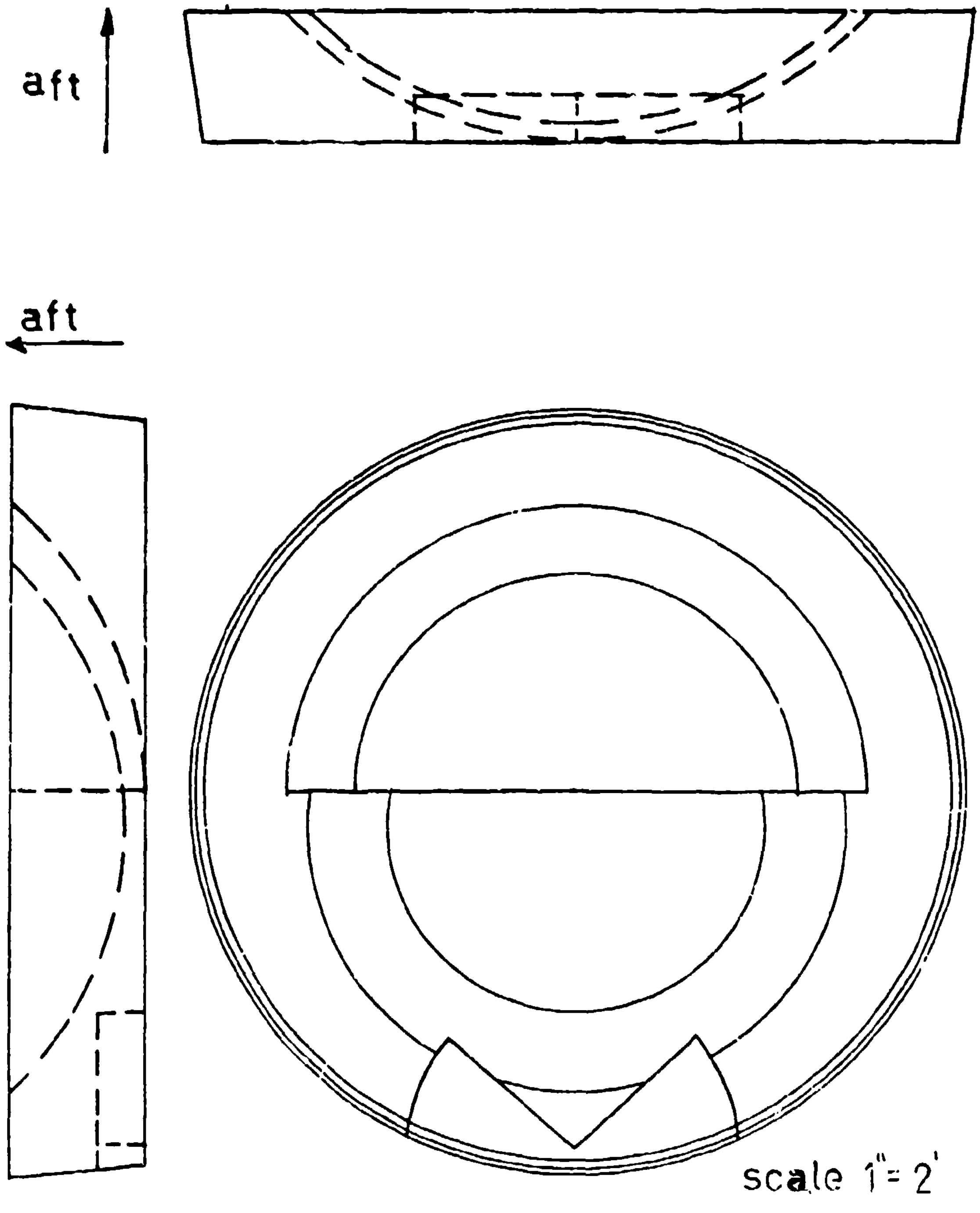


FIGURE 10-9 SECTION 6, 11.95' FWD. AP

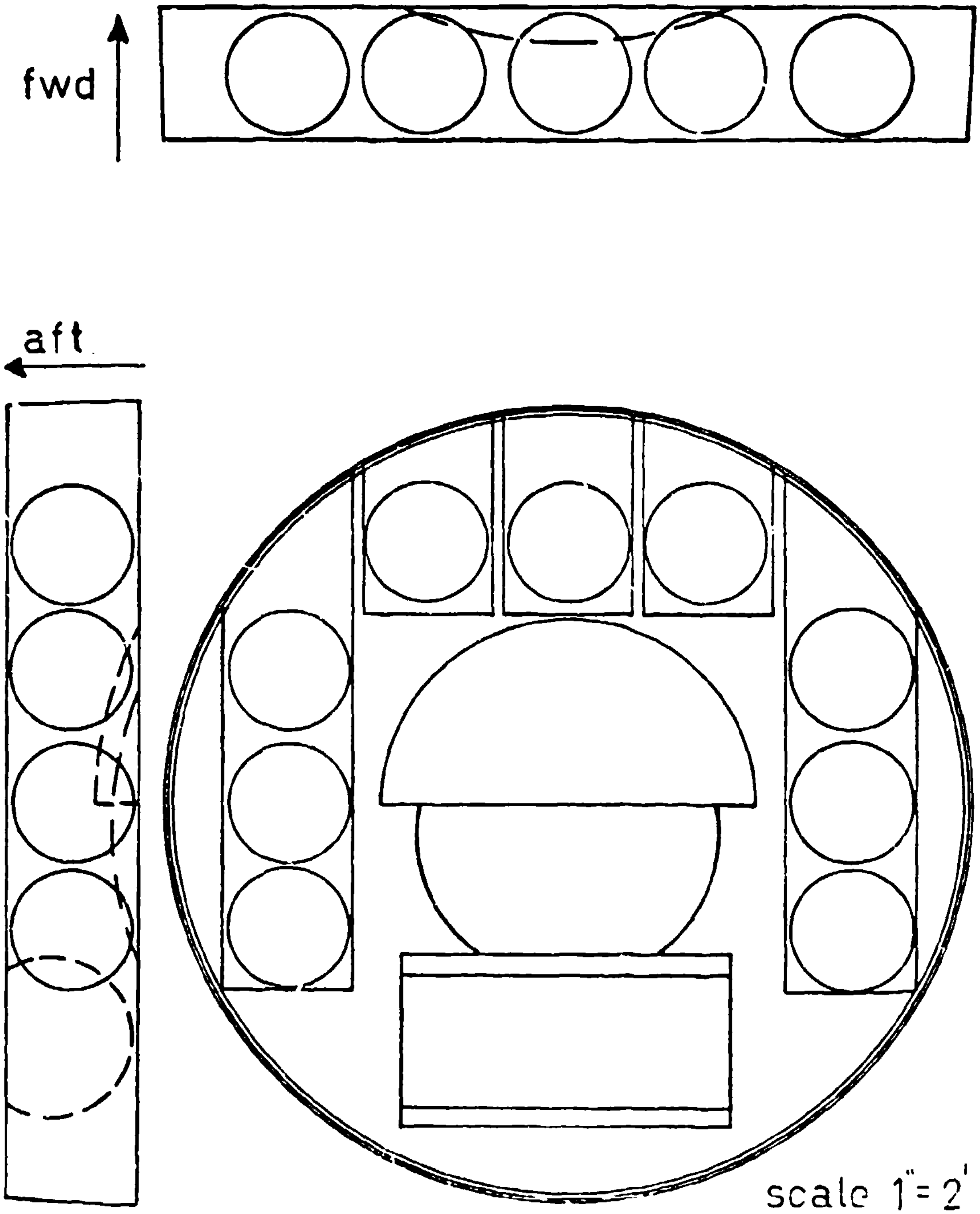


FIGURE 10-10 SECTION 7, 10.28′ FWD. AP

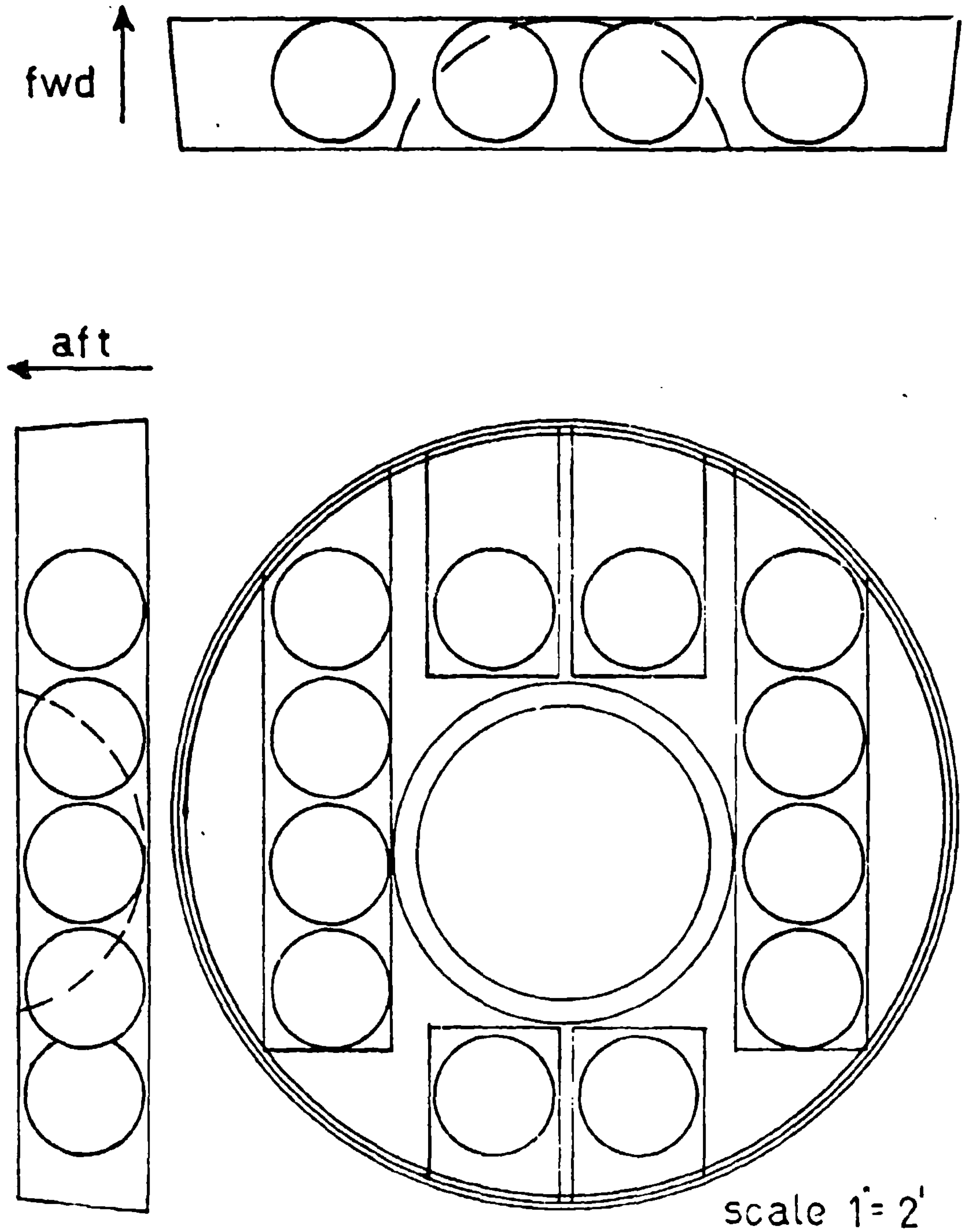


FIGURE 10-11 SECTION 8, 8.61' FWD. AP

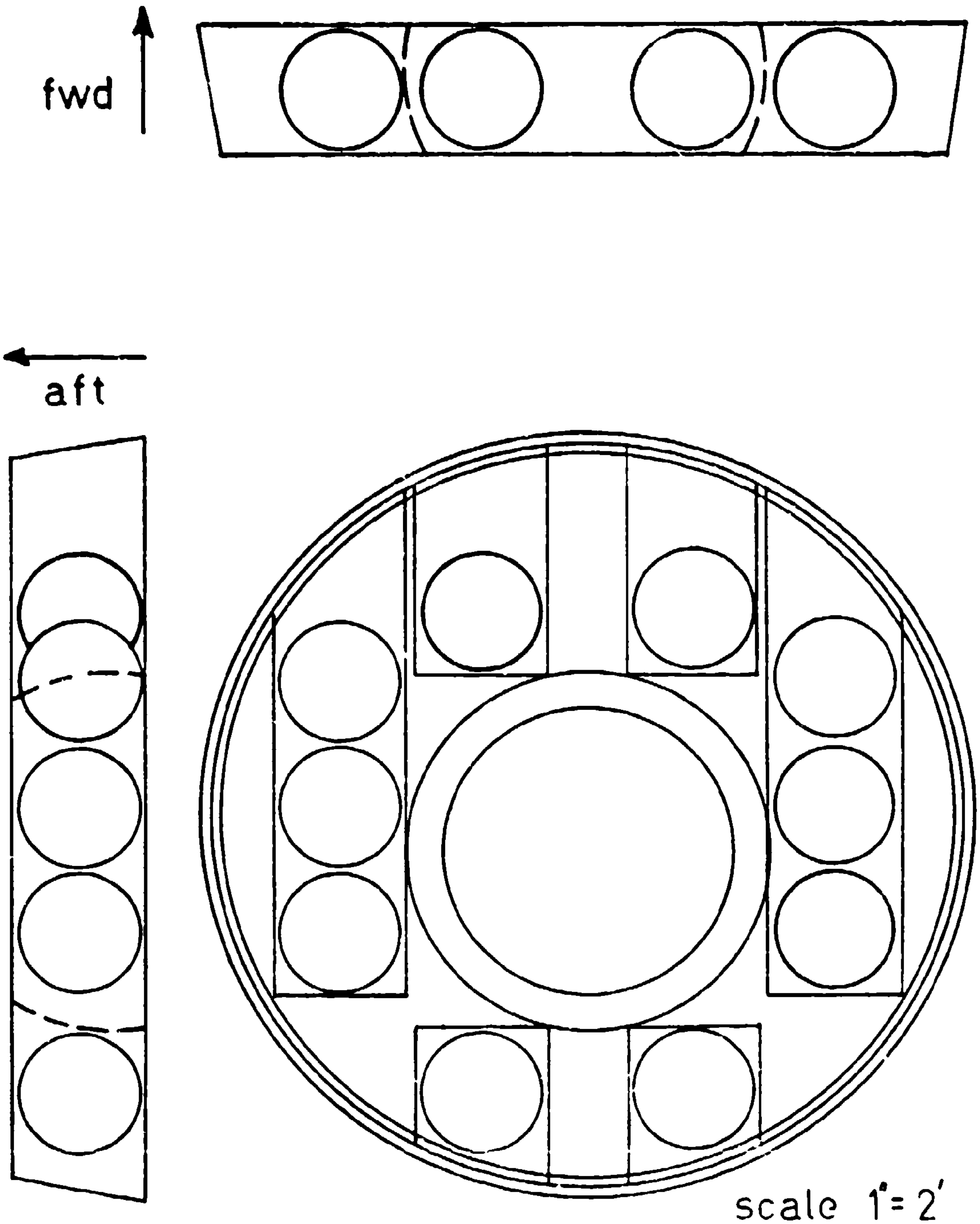


FIGURE 10-12 SECTION 9, 6.94' FWD. AP

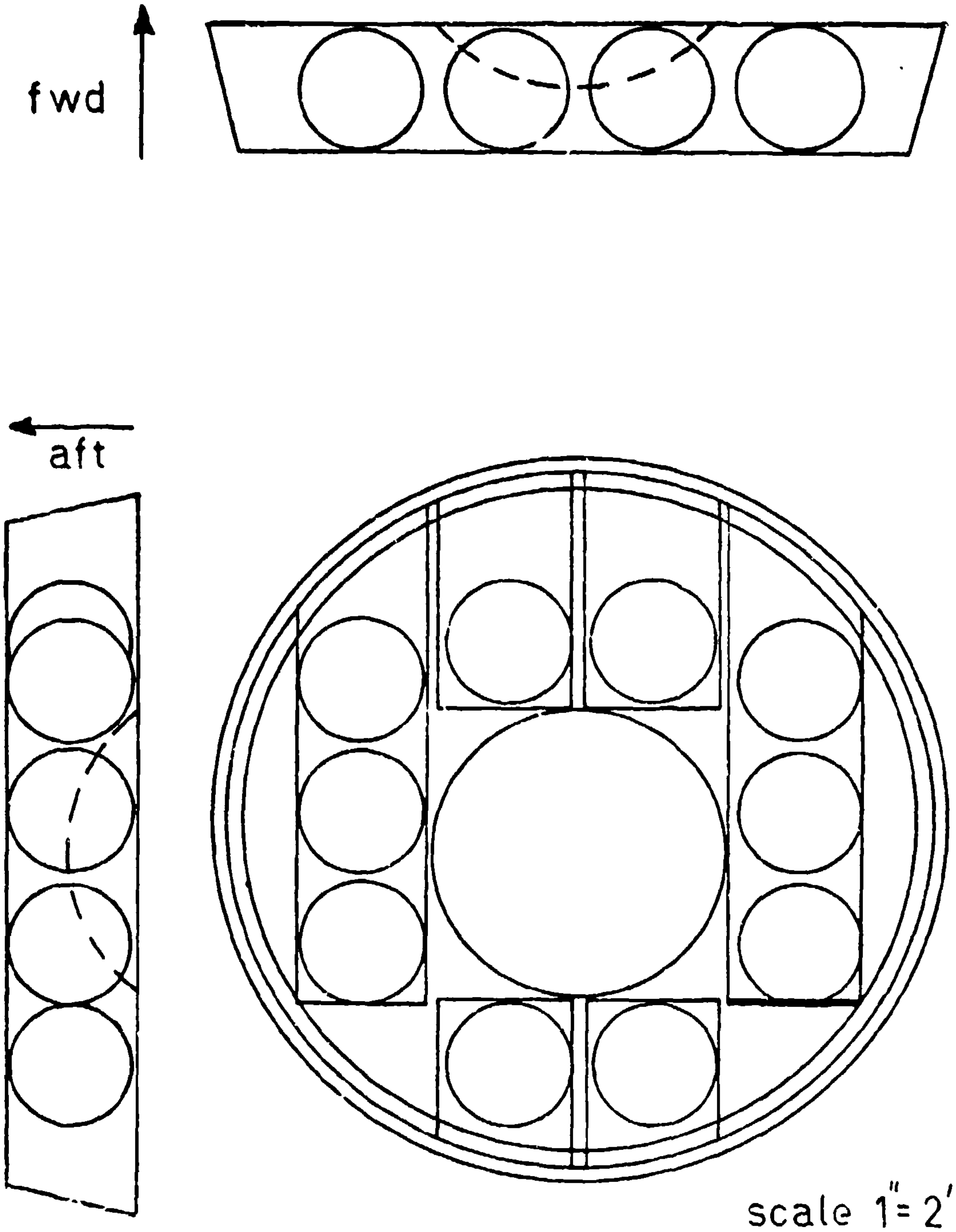


FIGURE 10-13 SECTION 10, 5.27' FWD. AP

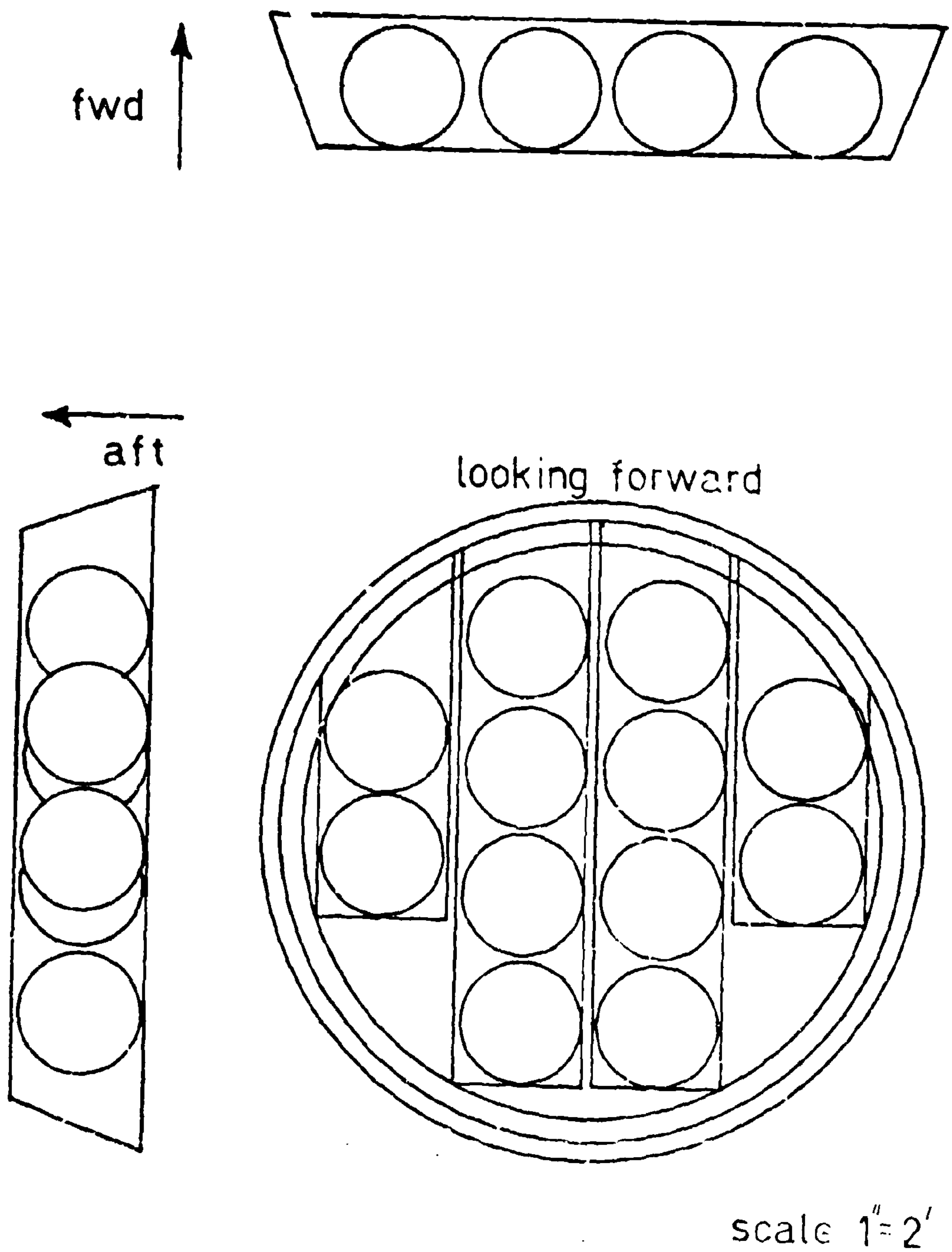
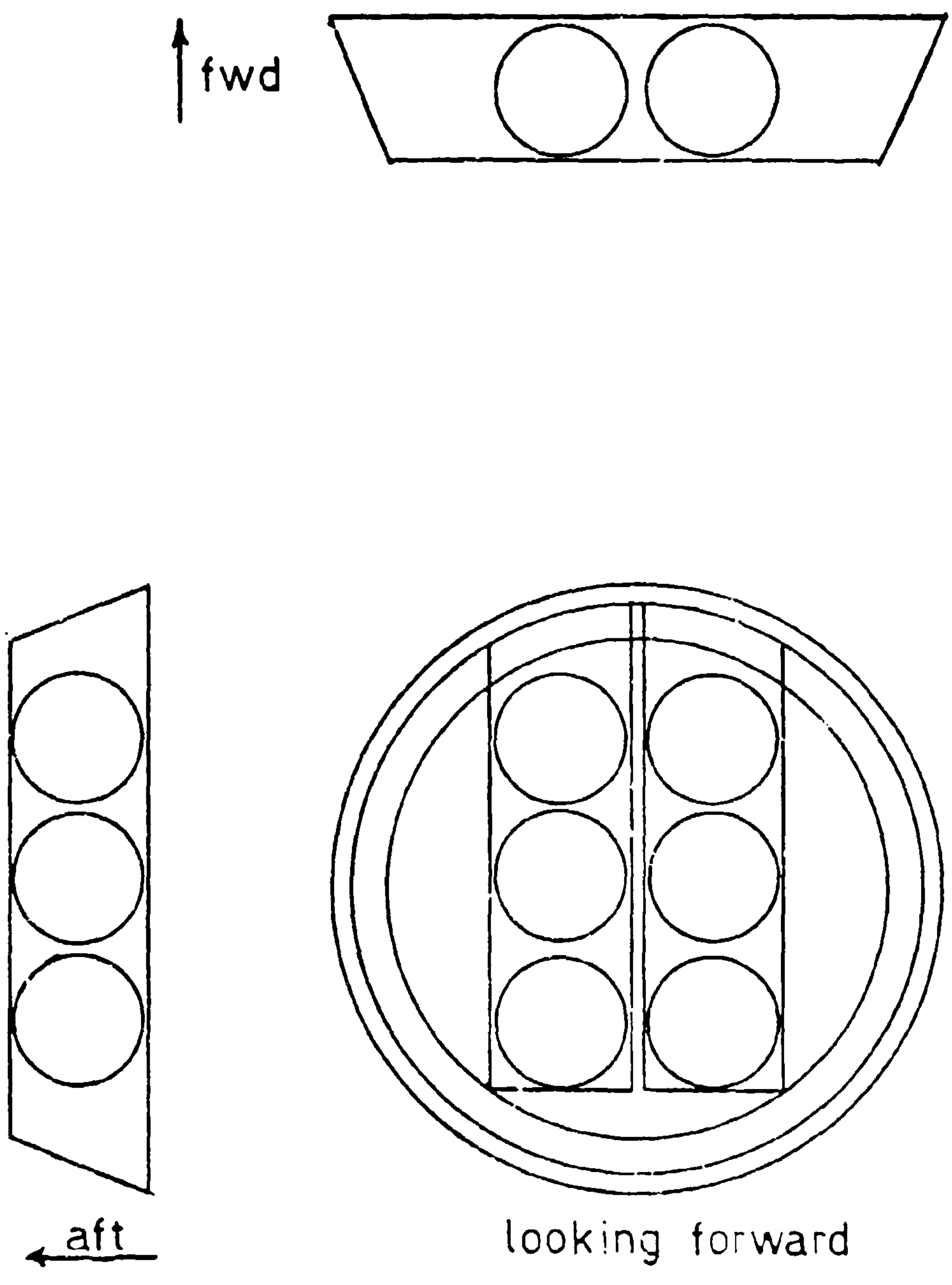


FIGURE 10-14 SECTION 11, 3.6′ FWD. AP



scale 1″=2′

maintenance required if some spheres were left empty and others fully loaded.

Providing storage space for ninety Case I battery jars results in total weight and displacement values of

$$W_I = (54.6)\ (90) = 4914\#$$

$$\Delta_I = (83.3)\ (90) = 7497\#$$

where, W_I is total weight of ninety Case I battery jars

Δ_I is total displacement of ninety Case I battery jars.

If a combination of some empty and some fully loaded spheres is used, its weight and displacement values must equal those of the Case I system. The components of the combination system are:

(1) Case III sphere: $W = 90.2\#$

$\Delta = 83.3\#$

(2) Empty sphere: $W = 37.5\#$

$\Delta = 83.3\#$

If, X = number of fully loaded spheres, and

90-X = number of empty spheres, then

$$\frac{W}{\Delta} = \frac{(90.2)(X) + (37.5)(90-X)}{(83.3)(X) + (83.3)(90-X)} = \frac{4914}{7497} = 0.656$$

Solving for X, the number of fully loaded spheres:

$$X = 29.2$$

The mixed system would therefore consist of twenty-nine fully loaded spheres and sixty-one empty ones. Since the storage capacity of a fully loaded sphere is 3.24 KWH, this implies a total storage capacity of 93.96 KWH, somewhat less than the previous system.

A combination of Case II battery jars and empty jars was investigated and it was found that thirty-three battery jars could be accommodated. The total storage capacity of this arrangement is 98.01 KWH or slightly more than the initial system that used all Case I battery jars.

These thirty-three battery jars must be placed so that the net resultant moments are the same for both the original Case I system and the composite Case II empty sphere system. Table 10.2 is a weight and moment sheet that describes the Case I system. It shows that the longitudinal center of gravity (LCG) of the Case I system is sixteen feet aft of the forward perpendicular (F.P.). The longitudinal center of buoyancy (LCB) is also sixteen feet aft of the forward perpendicular. Any combination system must have these same values of LCG and LCB. (It is noted that the LCB will not change).

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WEIGHT, DISPLACEMENT, MOMENT BALANCE SHEET

TABLE 10.2

ARCHITECT: ______

DATE: ______

SYSTEM CASE I

REF. LINE FOR LONGITUDINAL CENTERS IS PAGE ___ OF ___

REF. LINE FOR VERTICAL CENTERS IS 0.0 FEET ABOVE ~~BELOW~~ MOLDED BASELINE

0 . 0 FEET FORD AFT OF F. P.

Station	ITEM	WEIGHT LBS	VERT. LEVER FEET	VERT. MOMENT FT LBS	FORD LEVER FEET	FORD MOMENT FT LBS	DISPLACE-MENT	VERT. LEVER FEET	VERT. MOMENT FT LBS	FORD LEVER FEET	FORD MOMENT FT LBS
1	1 CASE I SPHERE	54.6			1.9	104	83.3			1.9	158
2	5 " "	273.0			3.57	975	416.5			3.57	1487
3	9 " "	491.4			5.24	2580	749.7			5.24	3920
4	16 " "	873.6			6.91	6030	1332.8			6.91	9240
6	9 " "	491.4			17.5	8600	749.7			17.5	13100
7	12 " "	655.2			19.17	12600	999.6			19.17	19150
8	10 " "	546.0			20.84	11400	833.0			20.84	17380
9	10 " "	546.0			22.51	12300	833.0			22.51	18750
10	12 " "	655.2			24.18	15850	999.6			24.18	24100
11	6 " "	327.6			25.85	8450	499.8			25.85	12900
	TOTALS:	4914.0				78889	7497.0				120185

$$LCG = \frac{\text{Moments of Weight}}{\text{Weights}} = \frac{78889}{4914} = 16'$$

$$LCB = \frac{\text{Moments of Displacement}}{\text{Displacements}} = \frac{120185}{7497} = 16'$$

Table 10.3 gives the locating arrangement selected to achieve the required LCG value. Table 10.4 gives the resultant weights and moments.

Table 10.3 - Battery Jar Locations for Combination System

Station Number	1	2	3	4	5	6	7	8	9	10	11
Number of empty spheres	1	3	4	10	-	9	8	6	10	6	0
Number of Case II spheres	0	2	5	6	-	0	4	4	0	6	6

Placing the Case II battery spheres at the bottoms of the GRP tubes and the empty spheres near the top would tend to increase the distance between the vertical center of gravity (VCG) and the vertical center of buoyancy (VCB), thus increasing the stability of the boat.

A single scheme cannot be shown that will be satisfactory for all boats. Each different craft must have this type of energy storage system tailor-made.

The remaining two members of the DSV family are created by adding circular hull sections to the balanced thirty-two foot boat of Figure 10.2, to lengthen it. Lengths of forty and fifty feet are required for those two craft.

The circular hull sections are to be loaded with battery jars in GRP cylinders. Each battery compartment is to be 10.0 feet in diameter and 1.7 feet thick. A typical section is shown in Figure 10.15. Eighteen C-16 spheres can be carried in each, for a storage capacity of 58.32 KWH if Case III spheres are used.

TABLE 10.4

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WEIGHT, DISPLACEMENT, MOMENT BALANCE SHEET

ARCHITECT: ______

DATE: ______

SYSTEM COMBINATION OF CASE II & EMPTY SPHERES

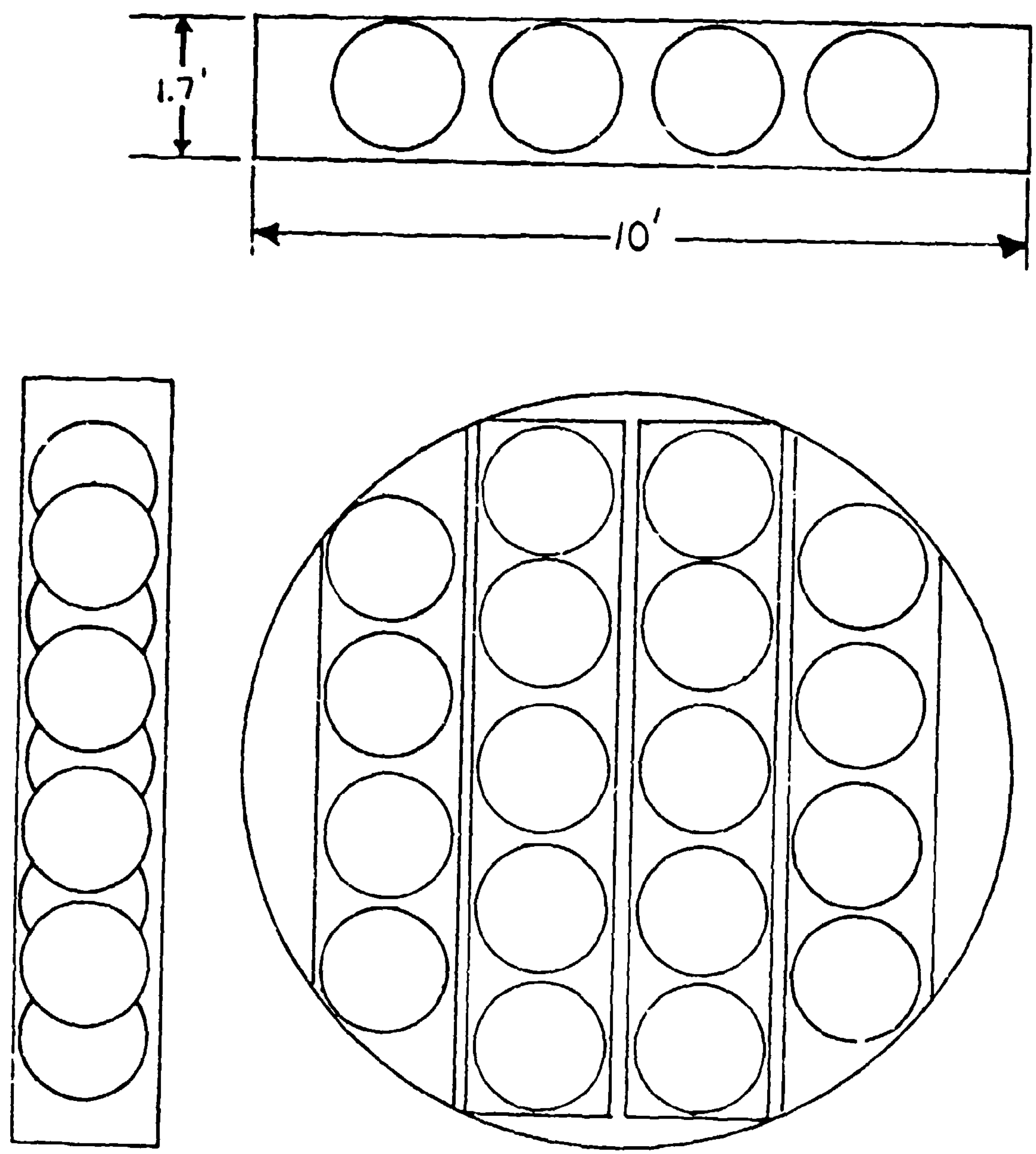
REF. LINE FOR LONGITUDINAL CENTERS IS PAGE ___ OF ___

REF. LINE FOR VERTICAL CENTERS IS 0.0 FEET ABOVE/BELOW MOLDED BASELINE

0 . 0 FEET FORD/AFT OF M. P.

Station	ITEM	WEIGHT LBS	VERT. LEVER FEET	VERT. MOMENT FT LBS	FORD LEVER FEET	FORD MOMENT FT LBS	DISPLACE-MENT	VERT. LEVER FEET	VERT. MOMENT FT LBS	FORD LEVER FEET	FORD MOMENT FT LBS
1	0 CASE II; 1 EMPTY	37.5			1.9	71	83.3			1.9	158
2	2 " ; 3 "	279.1			3.57	996	416.5			3.57	1,487
3	5 " ; 4 "	566.5			5.24	2970	749.7			5.24	3,920
4	6 " ;10 "	874.8			6.91	6045	1332.8			6.91	9,240
6	0 " ; 9 "	337.5			17.5	5906	749.7			17.5	13,100
7	4 " ; 8 "	633.2			19.17	12100	999.6			19.17	19,150
8	4 " ; 6 "	558.2			20.84	11533	833.0			20.84	17,380
9	0 " ;10 "	375.0			22.51	8440	833.0			22.51	18,750
10	6 " ; 6 "	724.8			24.18	17600	999.6			24.18	24,100
11	6 " ; 0 "	499.8			25.85	12850	499.8			25.85	12,900
	Subtotals:	4886.4				78511	7497.0				120,185
	Additional Ballast to Achieve W/Δ of 0.656	27.4			13.7	378	---			---	---
	TOTALS	4914.0				78889	7497.0				120,185

FIGURE 10-15 CIRCULAR ADD-ON BATTERY SECTION W/Δ = 1.0



scale 1" = 2'

Attention must be paid to the moment changes that result from separating the bow from the stern section. Separating the boat at the longitudinal center of gravity should result in two balanced halves. However, as shown in Figure 10.16, the LCG passes through the personnel sphere and main ballast tank. Weight must be added to the after half and buoyancy added to the forward half to compensate for the moment changes.

Five sections will be added between the forward and after halves to create a boat with a length overall of 40.5 feet. The energy storage capacity of the added compartments is 291.6 KWH, increasing the total amount of stored energy to 390 KWH.

Ten battery sections are to be added between the forward and after halves to create a boat with a length overall of 49 feet. The energy capacity of the added compartments is 583.2 KWH, increasing the total amount of stored energy to 681 KWH.

The total weight to displacement ratio of each added battery compartment must be 1.0, to maintain the balance of the boat. Table 10.5 summarizes a single section to insure $\frac{W}{\Delta} = 1.0$.

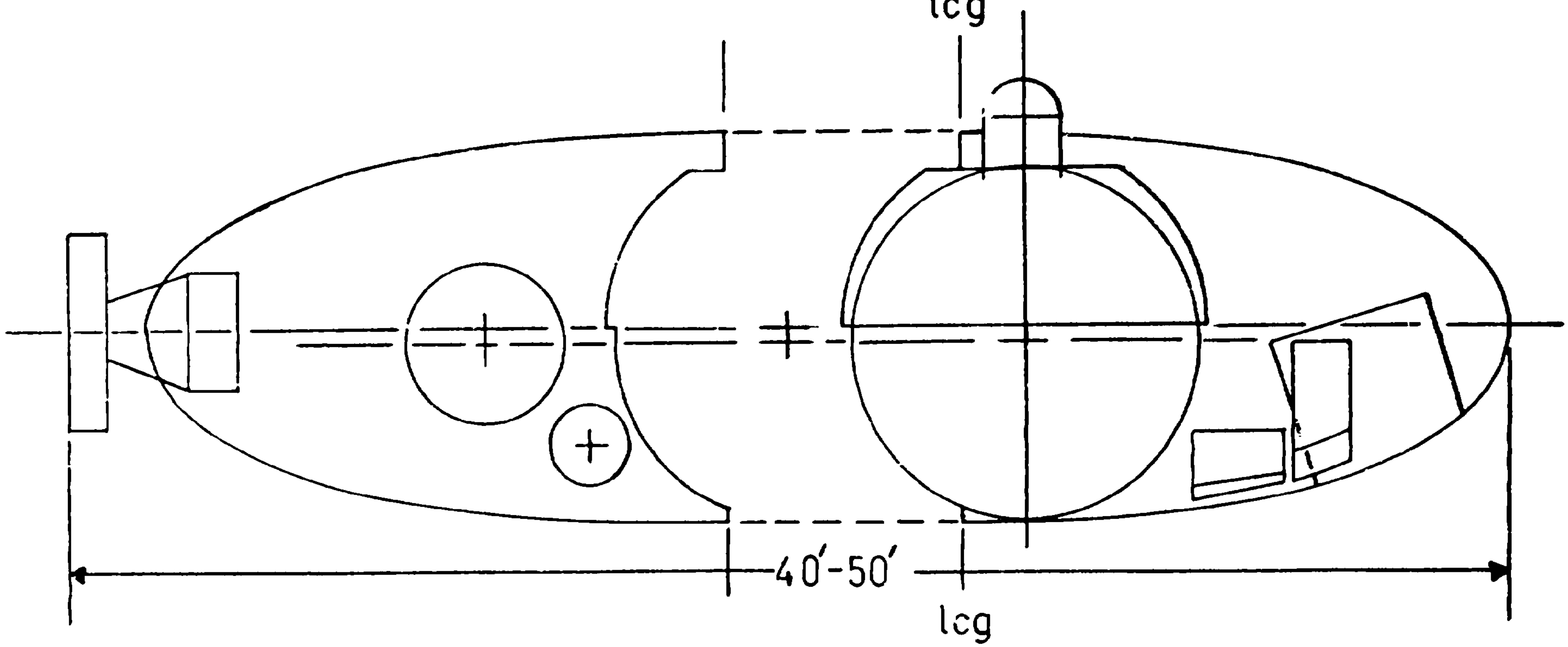


FIGURE 10-16 AN EXTENDABLE THIRTY TWO FOOT DSV

Table 10.5 - Weights and displacement of circular battery section

Item	W(lbs.)	Δ(lbs.)	Cost	
1/4" outer GRP skin	150	71	$ 225	$\frac{WH}{\#} = 19.5$
100' Cable & plugs	40	23	1,300	
18 Case III spheres	1578	1499	39,780	$\frac{WH}{ft.^3} = 1250$
GRP tubes	195	93	300	$\frac{WH}{\$} = 1.33$
Framing & structure	250	118	375	
Subtotals	2213	1804	$40,980	
18.6 $ft.^3$ of 42 PCF foam	781	1190	2,970	
Totals	2994	2994	$43,950	

The weight and displacement of the basic thirty-two foot craft would be increased by 14,970 pounds to create the forty foot DSV, and by 29,940 pounds to create the fifty-foot DSV.

Providing an additional 583 KWH using lead-acid batteries would require 540 cells weighing a total of 32,400 pounds. To achieve a weight to displacement ratio of 1.0 would require 735 $ft.^3$ of 42 PCF foam, weighing 30,870 pounds. The total displacement of that combination would be about 63,250 pounds, or 990 $ft.^3$. To fit within the ten foot diameter hull form, a compartment length of 12.6 feet is required.

CHAPTER XI

A DEMONSTRATION OF THE COMPETITIVENESS OF A A_gZ_n STORAGE SYSTEM WITH THE POPULAR PRESSURE COMPENSATED SYSTEM

The desirability of using a material other than steel as a pressure-proof container for an energy storage system was demonstrated in Chapter VI. That led to the development of the system under consideration: silver-zinc cells packaged in small pressure-proof glass spheres. This chapter will show the advantages of using the pressure-proof silver-zinc system rather than the popular pressure-compensated lead-acid type system.

In order to do this, systems of nearly equal storage capability will be outlined, and their system characteristics compared. The characteristics of interest are: (1) watthours per pound, (2) watthours per cubic foot, and (3) watthours per dollar. A storage capacity of 100 KWH will be used for each system. In addition, each of the competitive systems will be designed for the three cases of differing buoyancy as developed in Chapter VI. The pressure-proof silver-zinc system will be presented first.

<u>System I</u> - Silver-zinc cells in small pressure-proof glass spheres

<u>Case I</u> $\frac{W}{\Delta} = 0.656$

Since each C-16 sphere displaces 83.3 pounds, and the

required weight to displacement ratio is 0.656, the total allowable weight of a Case I sphere package is 54.6 pounds. The weight of each sphere and hatch covering is 37.5 pounds, leaving a payload capability of 17.1 pounds. The added weight of the penetrator is negligible because of the amount of material removed from the hatch covering for mounting that penetrator. Thus, eight LR-58 Silvercels(R) weighing 15.9 pounds can be accommodated, leaving 1.2 pounds for wire and supports. This package is summarized in Table 11.1.

Table 11.1 - Case I A_gZ_n pressure-proof package

Item	W(lbs.)	Δ(lbs.)	Cost
C-16 sphere	37.5	83.3	$ 325
8 LR-58 cells	15.9	----	560
penetrator	----	----	50
1/2 oz. platinum	----	----	75
wire & supports	1.2	----	2
Totals	54.6	83.3	$1,012

The capacity of one of these battery jars is 1.08 KWH. For the 100 KWH system, ninety-two such jars will be used, for an actual capacity of 99.36 KWH. That system is summarized in Table 11.2.

Table 11.2 - Case I A_gZ_n pressure-proof system

Item	W(lbs.)	Δ(lbs.)	Cost
92 spheres	3450.0	7664.6	$29,900
736 LR-58 cells	1463.0	----	51,520
92 penetrators	----	----	4,600
46 oz. platinum	----	----	6,900
wire & supports	110.0	----	184
Totals	5023.0	7664.6	$93,104

Case II $\frac{W}{\Delta} = 1.00$

Since each C-16 sphere displaces 83.3 pounds, and the required weight to displacement ratio is 1.00, the total allowable weight of a Case II sphere package is 83.3 pounds. The weight of each sphere is 37.5 pounds, leaving a payload capability of 45.8 pounds. Thus twenty-two LR-58 Silvercels(R) weighing 43.7 pounds can be carried, leaving 2.1 pounds for wire and supports. This package is summarized in Table 11.3.

Table 11.3 - Case II A_gZ_n pressure-proof package

Item	W(lbs.)	Δ(lbs.)	Cost
C-16 sphere	37.5	83.3	$ 325
22 LR-58 cells	43.7	----	1,540
penetrator	----	----	50
1 oz. platinum	----	----	150
wire & supports	2.1	----	5
Totals	83.3	83.3	$2,070

The capacity of a battery jar package such as that is 2.97 KWH. For the 100 KWH system, thirty-four battery jars will be used, for an actual capacity of 100.98 KWH. That system is summarized in Table 11.4.

Table 11.4 - Case II A_gZ_n pressure-proof system

Item	W(lbs.)	Δ(lbs.)	Cost
34 spheres	1275	2832	$11,050
748 LR-58 cells	1486	----	53,360
34 penetrators	----	----	1,700
34 oz. platinum	----	----	5,100
wire & supports	71	----	170
Totals	2832	2832	$71,380

Case III $\frac{W}{\Delta} = 1.05$

The buoyancy condition to be satisfied for a Case III package is that the system weight be greater than the system displacement. This is satisfied by packaging in a C-16 sphere the maximum number of cells that would physically fit. The resultant package houses twenty-four LR-58 Silvercels$^{(R)}$, weighing 47.7 pounds. The wiring and supports weight 2.5 pounds for a total package weight of 87.7 pounds. The weight to displacement ratio of that system is 1.05. This package is summarized in Table 11.5.

Table 11.5 - Case III $A_g Z_n$ pressure-proof package

Item	W(lbs.)	Δ(lbs.)	Cost
C-16 spheres	37.5	83.3	$ 325
24 LR-58 cells	47.7	----	1,680
penetrator	----	----	50
1 oz. platinum	----	----	150
wire & supports	2.5	----	5
Totals	87.7	83.3	$2,210

The capacity of a battery jar package such as this is 3.24 KWH. For the 100 KWH system, thirty-one battery jars will be used, for an actual capacity of 100.44 KWH. That system is summarized in Table 11.6.

Table 11.6 - Case III $A_g Z_n$ pressure-proof system

Item	W(lbs.)	Δ(lbs.)	Cost
31 C-16 spheres	1162.5	2582.3	$10,075
744 LR-58 cells	1478.7	----	52,080
31 penetrators	----	----	1,550
31 oz. platinum	----	----	4,650
wire & supports	77.5	----	155
Totals	2718.7	2582.3	$68,510

<u>System II</u> - Silver-zinc cells in a pressure-balanced enclosure.

For additional comparison, the design of a silver-zinc pressure compensated system will be shown. The basic system will consist of 736 LR-58 Silvercels(R) housed in a rectangular, oil-filled box. Various amounts of floatation material will be added to the basic unit in order to achieve the three cases of differing buoyancy.

The 736 LR-58 Silvercels(R) provide a storage capability of 99.36 KWH. These cells can be arranged in two layers of sixteen rows by twenty-three rows. The battery arrangement is shown in Figure 11.1. A one-inch thick slab of 20 PCF (pounds per cubic foot) foam will separate the battery layers with Dow Corning type 210 fluid filling the voids around the cells and forming a layer one inch thick at the top of the compartment. The container to house the cells will be made of 135 PCF GRP (glass reinforced plastic), 1/2 inch thick, and will have inside dimensions of 16.5" H × 52.0 L × 40.0" W. The outside dimensions are 17.5" H × 53.0" L × 41.0" W. That unit of the system is summarized in Table 11.7.

FIGURE 11-1 AG-ZN CELL ARRANGEMENT FOR PRESSURE-BALANCED SYSTEM

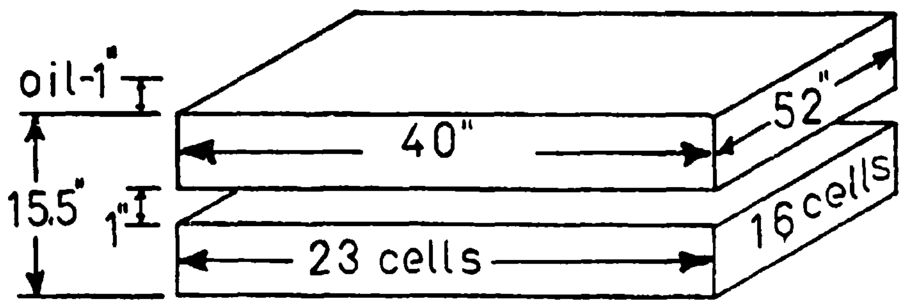


FIGURE 11-2 LEAD-ACID ARRANGEMENT FOR PRESSURE-BALANCED SYSTEM

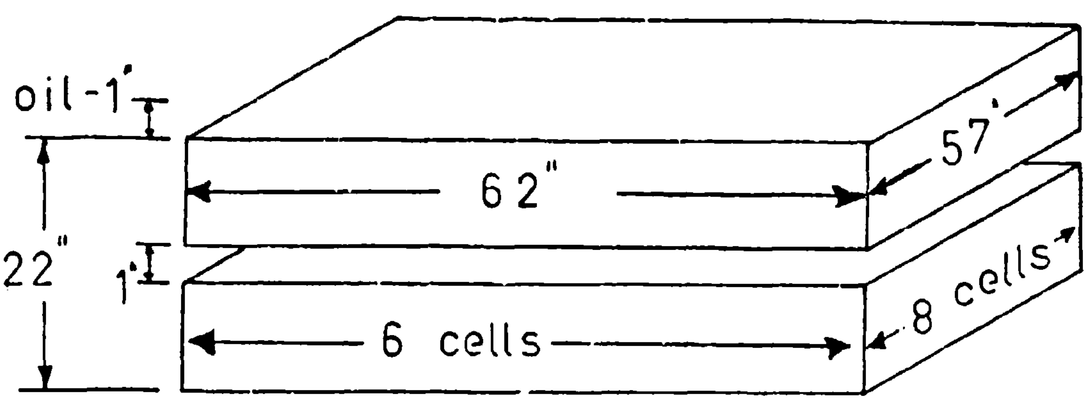


Table 11.7 - A_gZ_n pressure compensated package

Item	W(lbs.)	Δ(lbs.)	Cost
GRP box	1410	1860	$ 2,115
DC-210	96	----	480
separator	24	----	90
736 LR-58 cells	1463	----	51,520
Totals	2993	1860	$54,205

A considerable amount of floatation material must be added to that package to achieve the required weight to displacement ratios. This amount was found in the following manner:

$$\frac{W_s + W_f}{\Delta_s \quad \Delta_f} = \left(\frac{W}{\Delta}\right)_{\text{required}}$$

where, W_s = weight of system, 2993 pounds

Δ_s = displacement of system, 1860 pounds

W_f = weight of ad[illegible]oatation materi[illegible]l at 42 PCF

Δ_f = displaceme[illegible]ded floatation material at 64 PCF

$\left(\frac{W}{\Delta}\right)_{\text{required}}$ = requ[illegible] weight to displacement ratio

Letting A_f = volume of floatation material needed to achieve $\left(\frac{W}{\Delta}\right)_{\text{required}}$, and inserting the values of W_s, Δ_s, W_f, and Δ_f gives

$$\frac{2993 + 42\ A_f}{1860 + 64\ A_f} = \left(\frac{W}{\Delta}\right)_{\text{required}}$$

<u>Case II</u> $\frac{W}{\Delta} = 1.0$

To achieve a Case II buoyancy condition $(\frac{W}{\Delta}) = 1.00$), 51.5 cubic feet of floatation material (42 PCF foam) must be added to the basic package. That results in the system summarized in Table 11.11.

Table 11.11 - Case II A_gZ_n pressure-compensated system

Item	W(lbs.)	Δ(lbs.)	Cost
99.36 KWH package	2,993	1,860	$54,205
floatation material	2,163	3,296	8,600
Totals	5,156	5,156	$62,805

<u>Case III</u> $\frac{W}{\Delta} = 1.05$

To achieve a Case III buoyancy condition $(\frac{W}{\Delta} = 1.05)$, 41.6 cubic feet of floatation material (42 PCF foam) must be added to the basic package. That results in the system summarized in Table 11.12.

Table 11.12 - Case III A_gZ_n pressure-compensated system

Item	W(lbs.)	Δ(lbs.)	Cost
99.36 KWH package	2,992	1,860	$54,205
floatation material	1,757	2,662	6,677
Totals	4,750	4,522	$60,882

By using the $(\frac{W}{\Delta})_{required}$ corresponding to each of the three cases of differing buoyancy, the amount of foam required for each is determined. It should be noted that the $(\frac{W}{\Delta})_{required}$ for Case I cannot be obtained by using 42 PCF foam. Instead, 38 PCF foam will be used. The amount of foam required for each case is given in Table 11.8.

Table 11.8 - Amounts of foam needed to obtain $(\frac{W}{\Delta})_{required}$ for the A_gZ_n pressure-compensated system

	Case I	Case II	Case III
A_f (ft.^{3})	443	51.5	45.2
W_f (lbs.)	16,834	2163	1898
Δ_f (lbs.)	28,352	3296	2993
Cost	$70,700	$8600	$7212

<u>Case I</u> $\frac{W}{\Delta} = 0.656$

To achieve a Case I buoyancy condition ($\frac{W}{\Delta} = 0.656$), 443 cubic feet of floatation material (38 PCF foam) must be added to the basic package. That results in the system summarized in Table 11.10.

Table 11.10 - Case I A_gZ_n pressure-compensated system

Item	W(lbs.)	Δ(lbs.)	Cost
99.36 KWH package	2,993	1,860	$ 54,205
floatation material	16,834	28,352	70,700
Totals	19,827	30,212	$124,905

System III - Lead-acid batteries in a pressure-balanced enclosure

The pressure-balanced lead-acid type system is the least expensive, most commonly used type of energy storage for small submersibles. It is the major competition of the new pressure-proof silver-zinc concept. As was the case for the pressure-compensated silver-zinc system, a basic package housing lead-acid batteries will be developed. To that package, floatation material will be added to achieve the required weight to displacement ratios for Cases I, II, and III.

The storage element for this system will be the Exide 3-DFH-17 cell that was described earlier. Briefly, that cell weighs 60 pounds, costs $20, and can store 1080 watthours of energy.

For ease of arrangement, ninety-six cells will be used, providing a storage capacity of 103.68 KWH. These cells can be placed in two layers of six rows by eight rows. The battery arrangement will be as shown in Figure 11.12. A one-inch thick slab of 20 PCF foam will separate the battery layers, with Dow Corning type 210 fluid filling the voids around the cells and forming a layer one inch thick at the top of the compartment.

The container to house the batteries will be made of 135 PCF GRP, 1/2 inch thick, and will have inside dimensions of 23" H × 62" L × 57" W. The outside dimensions are

24" H × 63" L × 58" W. This package is summarized in Table 11.13.

Table 11.13 - lead-acid pressure-compensated package

Item	W(lbs.)	Δ(lbs.)	Cost
96 3-DFH-17 cells	5,760	----	$11,520
GRP box	2,144	3,495	3,216
separator	86	----	325
DC-210	215	----	430
Totals	8,205	3,495	$15,491

A considerable amount of floatation material must be added to that package to achieve the required weight to displacement ratios. This amount was found in the following manner:

$$\frac{W_s + W_f}{\Delta_s + \Delta_f} = \left(\frac{W}{\Delta}\right)_{\text{required}}$$

where, W_s = weight of system, 8205 pounds

Δ_s = displacement of system, 3495 pounds

W_f = weight of added floatation material at 42 PCF

Δ_f = displacement of added floatation material at 64 PCF

$\left(\frac{W}{\Delta}\right)_{\text{required}}$ = required weight to displacement ratio

Letting A_f = volume of floatation material needed to achieve $\left(\frac{W}{\Delta}\right)_{\text{required}}$, and inserting the values of W_s, Δ_s, W_f, and Δ_f gives:

$$\frac{8205 + 42\ A_f}{3495 + 64\ A_f} = \left(\frac{W}{\Delta}\right)_{\text{required}}$$

By using the $(\frac{W}{\Delta})_{required}$ corresponding to each of the three cases of differing buoyancy, the amount of floatation material needed for each is determined. It should be noted that the $(\frac{W}{\Delta})_{required}$ for Case I cannot be obtained by using 42 PCF foam. Instead 38 PCF foam will be used. The amounts of floatation material required for each case is given in Table 11.14.

Table 11.14 - Amounts of floatation material needed to obtain $(\frac{W}{\Delta})_{required}$ for the lead-acid pressure-compensated system

	Case I	Case II	Case III
A_f (ft.^{3})	1478.75	214.0	181.4
W_f (lbs.)	56,192	8,988	7,619
Δ_f (lbs.)	94,640	13,696	11,610
Cost	$214,000	$34,154	$28,952

<u>Case I</u> $\frac{W}{\Delta} = 0.656$

To achieve a Case I buoyancy condition ($\frac{W}{\Delta} = 0.656$), 1478.75 cubic feet of floatation material (38 PCF) must be added to the basic package. That results in the system summarized in Table 11.15.

Table 11.15 - Case I, lead-acid pressure-compensated system

Item	W(lbs.)	Δ(lbs.)	Cost
103.68 KWH package	8,205	3,495	$ 13,883
floatation material	56,192	94,640	214,000
Totals	64,397	98,135	$227,883

Case II $\frac{W}{\Delta} = 1.00$

To achieve a Case II buoyancy condition ($\frac{W}{\Delta} = 1.00$) 214 cubic feet of floatation material (42 PCF) must be added to the basic package. That results in the system summarized in Table 11.15.

Table 11.15 - Case II, lead-acid pressure-compensated system

Item	W(lbs.)	Δ(lbs.)	Cost
103.68 KWH package	8,205	3,495	$13,883
floatation material	8,988	13,696	34,154
Totals	17,193	17,191	$48,037

Case III $\frac{W}{\Delta} = 1.05$

To achieve a Case III buoyancy condition ($\frac{W}{\Delta} = 1.05$), 181.4 cubic feet of floatation material (42 PCF) must be added to the basic package. That results in the system summarized in Table 11.16.

Table 11.16-Case III, lead-acid pressure-compensated system

Item	W(lbs.)	Δ(lbs.)	Cost
103.68 KWH package	8,205	3,495	$13,883
floatation material	7,619	11,610	28,952
Totals	15,824	15,105	$42,835

In order to compare these systems, their energy densities and cost figures are presented in Table 11.17.

Table 11.17 - System characteristics of competitive energy storage concepts

System	W(lbs.)	Δ(lbs.)	Cost	W-H	WH/#	WH/ft.^{3}	WH/$
Case I							
A_gZ_n,PP	5,023	7,665	$ 93,104	99,360	19.8	826	1.07
A_gZ_n,PC	19,827	30,212	$124,905	99,360	5.0	220	0.79
P_b-acid,PC	64,397	98,135	$227,883	103,680	1.61	67.7	0.45
Case II							
A_gZ_n,PP	2,832	2,832	$ 71,380	100,980	35.8	2280	1.42
A_gZ_n,PC	5,156	5,156	$ 62,805	99,360	19.2	1230	1.59
P_b-acid,PC	17,193	17,193	$ 48,037	103,680	6.06	385	2.15
Case III							
A_gZ_n,PP	2,719	2,582	$ 68,510	100,440	37.0	2490	1.47
A_gZ_n,PC	4,750	4,522	$ 60,882	99,360	20.8	1400	1.62
P_b-acid,PC	15,824	15,105	$ 42,835	103,680	6.5	438	2.41

Examination of the data presented in Table 11.17 shows that the pressure-proof silver-zinc storage system exhibits the highest values of watthours per pound, watthours per cubic foot and watthours per dollar of any other Case I type system.

That shows the unmatched advantage of this "add-on" system. For the Case II and Case III conditions, the pressure-proof silver-zinc system leads the watthours per pound and watthours per cubic foot categories by substantial margins, while lagging only slightly behind the lead-acid system in the watthours per dollar category. These figures clearly demonstrate the superiority of the silver-zinc cell, packaged in small glass spheres for high energy density storage systems for deep ocean applications.

CHAPTER XII

CONCLUSIONS

This paper has demonstrated that a pressure-proof energy storage system using silver-zinc cells encapsulated in small glass spheres is a feasible way to provide electrical energy for deep submergence vehicles. That concept was fully developed, including the selection of optimum cell packaging arrangements for each of three cases of differing buoyancy.

The "add-on" concept of the Case I type battery jars is one of the principle advantages of that system. No other type of energy storage system has the ability of being directly substituted for the floatation material of a DSV.

The Case II battery jar is also of major importance for DSV energy storage. No other type of energy storage system can be installed in a DSV without requiring large amounts of floatation material.

The Case III battery jar is included for completeness. The light weight of the silver-zinc cells prevents the weight to displacement ratio of even a fully loaded sphere from becoming much larger than 1.00. As with conventional energy storage systems, a Case III system would require floatation material to achieve an overall weight to displacement ratio of 1.0. The Case III battery jar does have higher energy density values than the popular storage systems currently in use.

CHAPTER XIII

RECOMMENDATIONS

With the exception of fuel cells and nuclear reactors, the encapsulated silver-zinc concept represents the highest energy density storage system available for small submersibles. However, only a finite amount of energy is available from any given storage system. Further study seems warranted to determine the most efficient manner in which to expend that energy. For example, whether the power distribution should be DC, AC, or a combination of both needs to be established.

The concept of encapsulating silver-zinc cells in cast, foam spheres shows promise for use aboard shallow depth DSV's, and should be developed.

APPENDIX A

The information presented here was supplied by the battery manufacturing companies and is reproduced as an aid and convenience for further design work.

1. Eagle-Picher Industries, Inc. (Reference 7).

Information received from Eagle-Picher Industries indicates that they produce both nickel-cadmium and silver-zinc cells.

Their line of nickel-cadmium cells feature both vented and sealed types. A typical cell has an open circuit voltage of 1.3 volts and a working voltage of 1.0-1.2 volts. A reliable recycling capability in excess of five years is claimed. Table A.1 presents electrical and physical data on the vented type nickel cadmium cell.

Table A.1 - Eagle-Picher vented nickel-cadmium cell

Cell type	Capacity		Physical dimensions				Weight	Volume
	A-H	W-H	L	W	A	H	oz.	cubic in.
VNC 08	0.8	0.96	0.70	1.15	1.97	2.33	2.0	1.8
VNC 1.5	1.5	1.8	0.67	1.15	3.67	4.00	3.2	3.1
VNC 2A	2.0	2.4	0.72	1.50	3.06	3.43	4.0	3.7
VNC 2B	2.0	2.4	0.67	1.15	3.67	4.0	3.5	3.1
VNC 3	3.0	3.6	0.51	1.94	5.65	6.03	6.7	5.9
VNC 3.5	3.5	4.2	0.84	2.10	2.08	2.57	5.1	4.6
VNC 5.5A	5.5	6.6	0.94	2.17	3.62	4.02	9.0	8.2
VNC 5.5B	5.5	6.6	1.06	2.31	2.43	2.92	8.8	7.1
VNC 9	9.0	10.8	1.06	2.31	3.79	4.28	12.0	10.5
VNC 14	14.0	16.8	1.07	2.32	5.19	5.75	17.0	14.2
VNC 15	15.0	18.0	1.07	2.42	6.28	6.95	21.0	18.0
VNC 20A	20.0	24.0	1.07	3.18	6.13	6.62	26.0	22.5
VNC 20B	20.0	24.0	1.06	2.31	7.00	7.49	26.0	18.3
VNC 22	22.0	26.4	1.07	3.18	7.61	8.20	34.0	27.9
VNC 30	30.0	36.0	1.07	3.18	9.55	10.04	42.0	34.2
VNC 37	37.0	44.4	1.39	3.13	8.69	9.40	52.0	40.3
VNC 42	42.0	50.4	1.39	3.13	8.69	9.40	56.0	40.3
VNC 75	75.0	90.0	1.77	4.77	7.00	7.40	87.0	62.5

The rated capacity is based on the two hour discharge rate to one volt at 80° F. Weight and volume figures include terminals and vents.

Table A.2 presents electrical and physical data on the hermetically sealed type nickel-cadmium cell.

Table A.2 - Eagle-Picher sealed nickel-cadmium cell

Cell type	Capacity		Physical dimensions				Weight	Volume
	A-H	W-H	L	W	A	H	oz.	cubic in.
RSN 3	3.2	3.84	0.84	2.10	2.08	2.57	6.5	4.6
RSN 6	6.0	7.2	0.84	2.10	3.36	3.85	11.2	6.8
RSN 6B	6.0	7.2	1.07	3.18	2.75	3.25	12.7	11.0
RSN 8	8.0	9.6	1.00	2.06	4.00	4.62	15.2	9.14
RSN 9	9.0	10.8	1.06	2.31	3.79	4.28	15.7	10.5
RSN 14	14.0	16.8	1.06	2.31	5.19	5.75	21.4	14.2
RSN 15	15.0	18.0	1.47	3.19	3.62	4.25	25.5	20.0
RSN 20	25.0	30.0	1.47	3.19	4.75	5.38	36.6	25.2
RSN 22	22.5	27.0	1.07	3.18	6.13	6.62	37.0	22.5
RSN 36	36.0	43.2	1.47	3.19	5.75	6.38	44.8	29.8
RSN 36B	36.0	43.2	1.07	3.18	9.55	10.04	56.0	34.2

The rated capacity is based on the two hour discharge rate to one volt at 80° F. Weight and volume figures include terminals.

The Eagle-Picher line of silver zinc batteries are available as pre-packaged systems, rather than as individual cells. These packages are designed for space flight application and would require some modification in packaging to be of use in small pressure-proof vessels. Each package is described on a numbered data sheet and will be referred to by that number, since they are designated by the space vehicle

for which they were built. The systems are described here to give a representative sample of available cells. Physical and electrical information on these systems is given in Table A.3.

Table A.3 - Eagle-Picher silver-zinc pre-packaged systems

Data Sheet number	Capacity A-H	Capacity W-H	Phys. dimensions L	Phys. dimensions W	Phys. dimensions D	Weight (lbs.)	Volume (in.^{3})	Operating voltage
4265	53.0	1430	11.77	5.75	6.87	28.5	465	27.0
4248	2.0	50	5.45	2.63	2.62	2.0	35.3	25.0
4146	35.0	945	10.96	5.75	6.56	22.0	413	27.0
4144	45.0	1080	7.90	5.60	6.38	20.0	290	24.0

2. ESB Incorporated, Exide Industrial Division. (Reference 9).

The Exide Industrial Division of ESB Incorporated manufactures both lead-acid and silver-zinc type storage batteries. Exide Sea Space(R) lead-acid batteries are used in the power systems of such craft as Alvin, Autec I, Autec II, Deep Quest, DSRV, Star I, Star II, and Trieste II. Some of the DSV's using the Exide silver-zinc cells are Aluminant, Moray, and NR-1.

Although ESB has manufactured silver-zinc cells for every major type of deep submergence vessels, until recently batteries of that type were not off-the-shelf items, and did not fall into the category of products that could be pre-priced. They now offer a line of individual silver-zinc cells as well as several models of lead-acid batteries. Table A.4 and Table A.5 present electrical and physical properties of some lead-acid and silver-zinc batteries.

Table A.4 - Exide type DMSC lead-acid batteries (Autec type). Average cell voltage 1.935 V.

Cell type	Rated capacity (AH)	Physical dimensions L	W	H	Weight (lbs.)	Volume (in.^{3})	W-H
DMSC 9	200	$3\frac{9}{16}$	$6\frac{3}{16}$	$18\frac{1}{2}$	40	408	387
DMSC 11	250	$4\frac{5}{16}$	$6\frac{3}{16}$	$18\frac{1}{2}$	49	495	484
DMSC 13	300	$5\frac{1}{16}$	$6\frac{3}{16}$	$18\frac{1}{2}$	58	574	581
DMSC 15	350	$5\frac{7}{8}$	$6\frac{1}{4}$	$18\frac{1}{2}$	66	680	677
DMSC 17	400	$6\frac{5}{8}$	$6\frac{1}{4}$	$18\frac{1}{2}$	75	775	774
DMSC 19	450	$7\frac{3}{8}$	$6\frac{1}{4}$	$18\frac{11}{16}$	86	860	871
DMSC 21	500	$8\frac{1}{8}$	$6\frac{1}{4}$	$18\frac{11}{16}$	94	948	968
DMSC 23	550	$8\frac{7}{8}$	$6\frac{1}{4}$	$18\frac{11}{16}$	102	1035	1064
DMSC 25	600	$9\frac{5}{8}$	$6\frac{1}{4}$	$18\frac{11}{16}$	112	1130	1161
DMSC 27	650	$10\frac{3}{8}$	$6\frac{1}{4}$	$18\frac{11}{16}$	120	1210	1258
DMSC 29	700	$11\frac{1}{8}$	$6\frac{1}{4}$	$18\frac{11}{16}$	128	1300	1355
DMSC 33	800	$12\frac{5}{8}$	$6\frac{1}{4}$	$18\frac{11}{16}$	145	1480	1548
3-DFH-17	150	$10\frac{5}{16}$	$7\frac{1}{8}$	$10\frac{3}{16}$	60	748	900

Table A.5 - Exide type DS silver-zinc batteries

Cell type	Rated Capacity		Physical dimensions			Weight	Volume
	A-H	W-H	L	W	H	(Lbs.)	(in.^{3})
DS 2.5	2.5	3.7	.56	1.38	2.48	.15	1.92
DS 5	5	7.4	.71	1.76	2.96	.25	3.7
DS 7.5	7.5	11.1	.80	2.08	3.00	.50	5.0
DS 10	10	15.0	.89	2.21	3.86	.60	7.6
DS 25	25	37.0	.75	2.06	4.28	1.00	7.1
DS 50	50	74.0	.97	3.50	7.12	2.00	24.2
DS 100	100	150	3.43	2.78	4.69	2.8	44.6
DS 200	200	290	2.76	3.04	11.38	7.5	95.5
DS 400	400	590	1.93	5.78	17.43	14.0	195
DS 650	650	960	1.93	5.78	25.31	22.0	281
DS 850	850	1260	4.70	4.50	17.75	29.5	376
DS 27000	27000	40000	14.00	12.00	54.00	875	9072

Rates based on 6 hour discharge

3. General Electric Company. (Reference 12).

Correspondence with GE disclosed that they do not manufacture lead-acid batteries. The battery business section of that company at the present time is devoted exclusively to the production of nickel-cadmium cells. A representative sample of their product is shown in Table A.6.

Table A.6 - GE nickel-cadmium cells. (1.2 V average)

Cell type	Capacity A-H	Capacity W-H	Physical dimensions L	Physical dimensions W	Physical dimensions H	Weight (lbs.)	Volume (in.^{3})
43B011AC02	11	13.2	2.4	1.1	6.9	1.2	18.2
43B022AC02	12	14.4	3.2	1.1	8.2	2.0	28.9
43B034AC01	34	40.8	3.1	1.4	9.3	3.5	40.4
43B070AC01	70	84.0	5.0	1.9	8.1	7.0	77.0
43B085AA01	85	102	5.9	2.6	7.9	9.1	121
43B100AA01	100	120	5.9	3.2	8.1	11.5	153
43B140AA01	140	168	5.9	4.4	8.1	14.9	210
43B170AA01	170	204	5.9	5.2	8.1	18.8	248
43B200AA01	200	240	5.9	6.3	8.1	22.2	301
43B360AA01	360	432	7.2	6.4	11.6	40.0	534

4. Yardney Electric Corporation. (Reference 27).

The Yardney Electric Company produces the most complete line of silver-cadmium and silver-zinc cells of any of the responding battery manufacturers. Yardney's line of silver zinc cells include both a high discharge rate type and a low discharge rate type. Table A.7 and Table A.8 give physical and electrical properties of the silver-cadmium and the low rate silver-zinc cells.

Table A.7 - Yardney silver-cadmium cells (1.1 V average)

Cell model	Capacity		Physical dimensions			Weight	Volume
	AH	WH	L	W	H	(oz.)	(in.^{3})
YS 20	26.0	28.6	2.05	1.73	4.28	15.1	15.2
YS 35	40.5	44.5	0.93	3.70	8.11	33.0	27.9
YS 40	48.0	52.8	0.99	3.25	7.05	26.3	22.7
YS 60	75.0	82.5	2.36	2.73	4.5	42.5	29.0
YS 70	80.0	88.0	1.41	3.64	6.25	42.0	32.1
YS 75	55.0	60.5	2.40	3.37	7.19	66.2	58.0
YS 85	100.0	110.0	1.81	2.81	9.44	61.0	48.4
YS 90	76.8	84.5	2.16	3.25	7.06	51.8	49.6
YS 100	115.0	126.5	3.44	2.78	4.81	53.0	46.0
YS 140	95.2	105.0	2.86	3.25	7.22	79.2	67.1
YS 150	165.0	181.5	1.78	4.19	10.72	109.0	79.8
YS 300	360.0	396.0	1.78	4.19	17.5	183.0	131.0

Amp hour output is to a final voltage of 0.6 V.

Watthour figured on basis of average voltage of 1.1 V.

Overall volume includes terminals.

Height includes terminals.

Table A.8 - Yardney silver-zinc low rate cells (1.5 V average)

Cell model	Capacity		Physical dimensions			Weight	Volume
	A-H	W-H	L"	W"	H"	(oz.)	(in.^{3})
LR 20	30.0	45.0	1.73	2.05	4.28	14.0	15.2
LR 21	30.0	45.0	0.80	2.30	7.53	15.5	13.9
LR 40	46.0	69.0	0.99	3.25	7.09	23.0	22.8
LR 58	90.0	135.0	1.27	3.25	7.25	31.8	29.9
LR 60	65.0	97.5	2.36	2.73	4.50	29.0	29.0
LR 70	80.0	120.0	1.41	3.64	6.25	40.0	32.1
LR 85	140.0	210.0	1.81	2.81	9.44	62.0	48.0
LR 90	145.0	217.5	2.16	3.26	7.06	57.1	49.7
LR 100	110.0	165.0	2.78	3.44	4.81	44.0	46.1
LR 130	170.0	255.0	2.50	3.275	6.55	62.8	53.8
LR 200	225.0	337.5	1.31	5.87	11.3	102.5	88.0
LR 300	330.0	495.0	1.78	4.19	17.5	150.0	131.0

Amp hour output is to a final voltage of 1.1 V.

Watthour capacity figured on a basis of average voltage 1.5 V.

Overall volume includes terminals.

Height includes terminals.

A P P E N D I X B

The information presented here was supplied by the battery manufacturing companies and is reproduced as an aid and convenience for further design work.

Table B.1 - Energy densities of Eagle-Picher vented nickel cadmium cells

Cell Type	VNC 0.8	VNC 1.5	VNC 2.0B	VNC 3	VNC 3.5	VNC 5.5A	VNC 5.5B	VNC 9	VNC 14	VNC 15	VNC 20B	VNC 22	VNC 30	VNC 37	VNC 42	VNC 75
W/H Cap.	.96	1.8	2.4	3.6	4.2	6.6	6.6	10.8	16.8	18.0	24.0	26.4	36.0	44.4	50.4	90.0
Wt. (oz.)	2.0	3.2	3.5	6.7	5.1	9.0	8.8	12.0	17.0	21.0	26.0	34.0	42.0	52.0	56.0	87.0
Vol. $in.^3$	1.8	3.1	3.1	5.9	4.6	8.2	7.1	10.5	14.2	18.0	18.3	27.9	34.2	40.3	40.3	62.5
W/H lb.	7.68	9.0	11.0	8.6	13.2	11.8	12.0	14.4	15.8	13.7	14.8	12.4	13.7	13.7	14.4	16.5
W/H $in.^3$	0.53	0.58	0.775	0.61	0.91	0.81	0.93	1.03	1.18	1.0	1.31	0.945	1.05	1.1	1.25	1.44

Table B.2 - Energy densities of Eagle-Picher sealed nickel-cadmium cells

Cell Type	RSN 3	RSN 6	RSN 6B	RSN 8	RSN 9	RSN 14	RSN 15	RSN 20	RSN 22	RSN 36	RSN 36B
W/H Capacity	3.84	7.2	7.2	9.6	10.8	16.8	18.0	30.0	27.0	43.2	43.2
Weight (oz.)	6.5	11.2	12.7	15.2	15.7	21.4	25.5	36.6	37.0	44.8	56.0
Volume ($in.^3$)	4.6	6.8	11.0	9.14	10.5	14.2	20.0	25.2	22.5	29.8	34.2
W/H lb.	9.45	10.3	9.1	10.1	11.0	12.6	11.3	13.1	11.7	15.4	12.3
W/H $in.^3$	0.835	1.06	0.66	1.05	1.03	1.18	0.9	1.19	1.2	1.45	1.26

Table B.3 - Energy densities of Eagle-Picher silver-zinc battery package

Package Type	4265	4248	4146	4144
W/H capacity	1430	50	94.5	1080
Weight (lbs.)	28.5	2.0	22.0	20.0
Volume (in.^{3})	465	35.3	413	290
W/H (lb.)	50.2	25.0	43.0	54.0
W/H (in.^{3})	3.07	1.41	2.28	3.72

Table B.4 and Table B.5 show the energy densities of the Exide lead-acid and silver-zinc type storage cells.

Table B.4 - Energy densities of Exide type DMSC lead-acid storage batteries

Cell type	DMSC 9	DMSC 11	DMSC 13	DMSC 15	DMSC 17	DMSC 19	DMSC 21	DMSC 23	DMSC 25	DMSC 27	DMSC 29	DMSC 33	3-DFH-17
W/H Cap.	387	484	581	677	774	871	968	1064	1161	1258	1355	1548	900
Wt. (lbs.)	40	49	58	66	75	86	94	102	112	120	128	145	60
Vol. (in.^{3})	408	495	574	680	775	860	948	1035	1130	1210	1300	1480	748
WH/lb.	9.7	9.9	10.0	10.3	10.3	10.1	10.3	10.4	10.4	10.5	10.6	10.7	15.0
WH/in.^{3}	.95	.98	1.01	.996	.996	1.01	1.02	1.03	1.05	1.04	1.04	1.04	1.2

Table B.5 - Energy densities of Exide type DS silver-zinc cells

Cell type	DS 2.5	DS 5	DS 7.5	DS 10	DS 25	DS 50	DS 100	DS 200	DS 400	DS 650	DS 850	DS 27,000
W/H Cap.	3.7	7.4	11.1	15.0	37.0	74.0	150	290	590	960	1260	40,000
Wt. (lbs.)	.15	.25	.50	.60	1.00	2.00	2.8	7.5	14.0	22.0	29.5	875
Vol. (in.^{3})	1.92	3.7	5.0	7.6	7.1	24.2	44.6	95.5	195	281	376	9072
WH/lb.	24.6	29.6	22.2	25.0	37.0	37.0	53.5	38.7	42.1	43.5	42.8	45.6
Wh/in.^{3}	1.93	2.0	2.22	1.97	5.2	3.06	3.36	3.04	3.02	3.4	3.36	5.03

Table B.6 shows the energy densities for the General Electric line of nickel-cadmium storage cells.

Table B.6 - Energy densities of General Electric nickel-cadmium cells

Cell type	43B011 AC02	43B022 AC02	43B034 AC01	43B070 AC01	43B085 AA01	43B100 AA01	43B140 AA01	43B170 AA01	43B200 AA01	43B360 AA01
W/H Cap.	13.2	14.4	40.8	34.0	102.0	120.0	168.0	204.0	240.0	432.0
Wt. (lbs.)	1.2	2.0	3.5	7.0	9.1	11.5	14.9	18.8	22.2	40.0
Vol. (in.^{3})	18.2	28.9	40.4	77.0	121.0	153	210	248	301	534
WH/lb.	11.0	7.2	11.7	12.0	11.2	10.4	11.3	10.8	10.8	10.8
WH/in.^{3}	0.725	0.50	1.01	1.09	0.84	0.785	0.80	0.82	0.798	0.81

Table B.7 and Table B.8 present the energy densities of the Yardney Electric Company's silver-cadmium and silver-zinc type storage cells.

Table B.7 - Energy densities of Yardney silver-cadmium cells

Cell type	YS 20	YS 35	YS 40	YS 60	YS 70	YS 75	YS 85	YS 90	YS 100	YS 140	YS 150	YS 300
W/H Cap.	28.6	44.5	52.8	82.5	88.0	60.5	110.0	84.5	126.5	105.0	181.5	396.0
Wt. (oz.)	15.1	33.0	26.3	42.5	42.0	66.2	61.0	51.8	53.0	79.2	109.0	183.0
Vol. (in.^{3})	15.2	27.9	22.7	29.0	32.1	58.0	48.4	49.6	46.0	67.1	79.8	131.0
WH/lb.	30.3	21.6	32.2	31.1	33.5	14.6	28.9	26.1	38.2	21.2	26.6	34.6
WH/in.^{3}	1.88	1.59	2.32	2.84	2.74	1.04	2.29	1.70	2.76	1.56	2.28	3.02

Table B.8 - Energy densities of Yardney silver-zinc cells

Cell type	LR 20	LR 21	LR 40	LR 58	LR 60	LR 70	LR 85	LR 90	LR 100	LR 130	LR 200	LR 300
W/H Cap.	45.0	45.0	69.0	135.0	97.5	120.0	210.0	217.5	165.0	255.0	337.5	495.0
Wt. (oz.)	14.0	15.5	23.0	31.8	29.0	40.0	62.0	57.1	44.0	62.8	102.5	150.0
Vol. (in.^{3})	15.2	1[illegible].9	22.8	29.9	29.0	32.1	48.0	49.7	46.1	53.8	88.0	131.0
W/H lb.	51.4	46.5	48.0	68.0	5[illegible].8	48.0	54.3	60.8	59.9	65.0	52.6	52.8
W/H in.^{3}	2.96	3.24	3.02	4.5	3.[illegible]6	3.74	4.38	4.37	3.58	4.74	3.83	3.78

APPENDIX C

To enclose a single lead-acid battery in a pressure-proof sphere the length of the major diagonal of the battery determines the diameter of the sphere. The length of the diagonal for the Exide 3-DFH-17 battery is 16.2". Therefore, the cell can be enclosed within a sphere having an inside diameter of 16.2 inches. A sphere is designed to the following parameters (Reference 14):

inside radius: $R_i = 8.1"$

material: HY-80, $\delta ys = 80$ ksi

operating depth: 20,000', 9030 psi

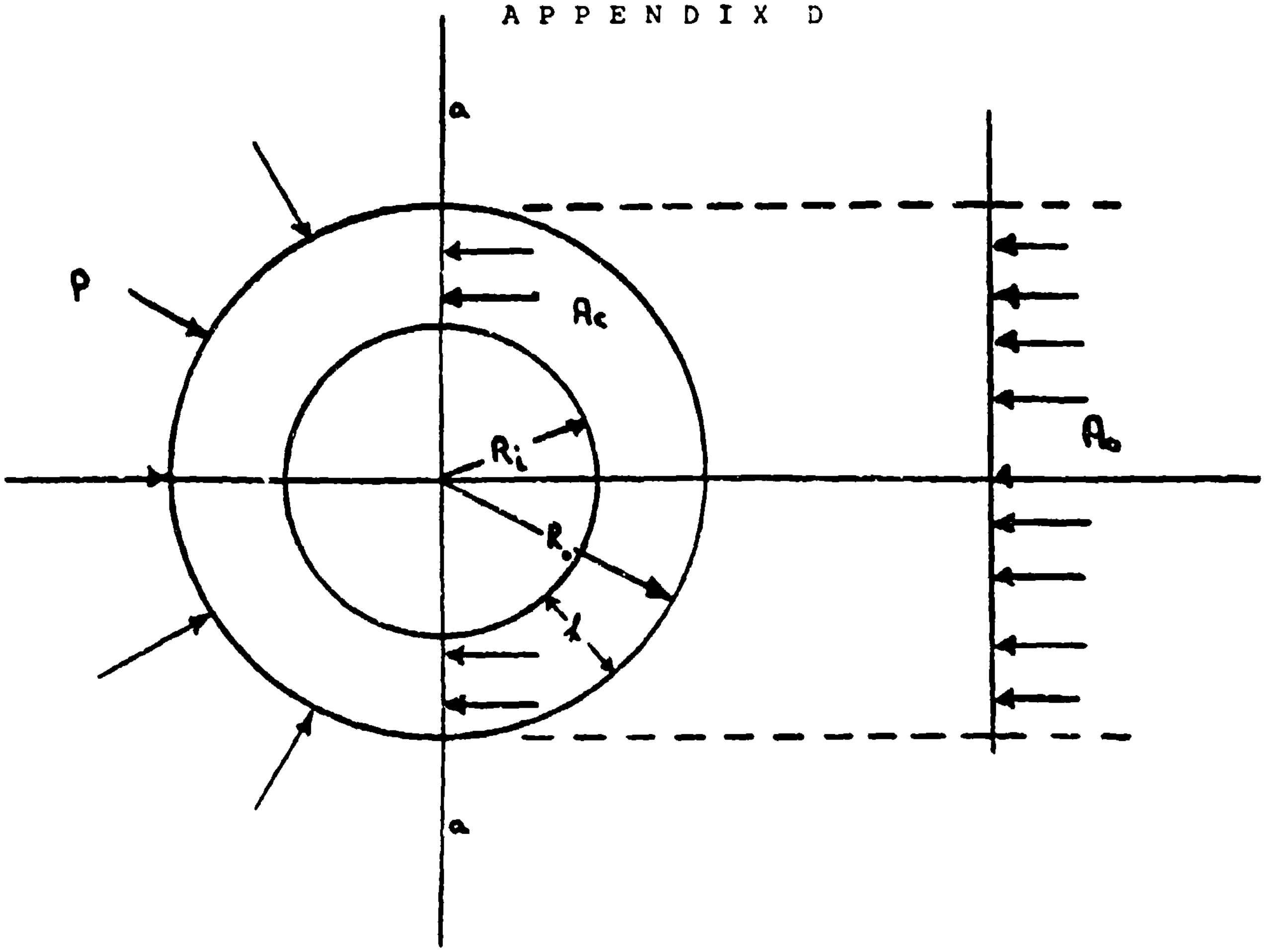
collapse depth: 30,000', 13545 psi

$\delta ave \leq \frac{2}{3} \delta ys$: $\delta ave \leq 53.3$ ksi

Use of these parameters results in a sphere whose thickness, h, is one inch. The volume of material in that sphere is 930 cubic inches. The weight of the sphere, W_s, is thus 265 pounds. The displacement of the sphere in salt water, Δ_s, is 117 pounds. The weight to displacement ratio of the empty sphere is $\frac{W_s}{\Delta_s} = \frac{265}{117} = 2.26$, or negatively buoyant. The weight to displacement ratio of the sixty-pound battery and sphere would be

$$\frac{W_s + 60\#}{\Delta_s} = \frac{325}{117} = 2.78$$

APPENDIX D



where, A_c - area of ring at equatorial section

A_o - flat plate frontal area

p - external pressure

R_i - cavity radius

R_o - radius to outside of sphere

h - wall thickness

$$\text{stress at section a-a} = \frac{\text{(force at a-a)}}{\text{(area a-a)}}$$

$$\delta = \frac{[(p)(A_o)]}{A_c} \qquad \text{(eq. D-1)}$$

$$\delta = \frac{p\ (\pi R_o^{\ 2})}{(\pi R_o^{\ 2} - \pi R_i^{\ 2}}$$

$$\delta = p \ \frac{R_o^{\ 2}}{R_o^{\ 2} - R_i^{\ 2}}$$

$$\delta = \frac{p(R_i + h)^2}{(R_i + h)^2 - R_i^{\ 2}}$$

$$\delta = \frac{p(R_i + h)^2}{R_i^{\ 2} + 2R_i h + h^2 - R_i^{\ 2}}$$

$$\delta = \frac{p(R_i + h)^2}{2R_i h + h^2} \qquad \text{(eq. D-2)}$$

This is the same result that is obtained by using $R_o = R_i + h$ and $R = R_i + \frac{h}{2}$ in the average membrane stress for spheres formula,

where, R_o = outside radius

R = radius to mid-surface

h = thickness

R_i = inside radius

p = external pressure

$$\delta = \frac{p}{2h}\,\frac{R_o^{\ 2}}{R}$$ - average membrane stress formula for spheres

Expanding eq. D-2, gives,

$$\delta = p\,\frac{(R_i^{\ 2}+2R_ih+2h^2)}{(2R_ih+h^2)} \qquad \text{(eq. D-3)}$$

It can be seen that the value of stress, δ, will always exceed the external pressure, p.

The physical parameters of the Emerson and Cummings floatation material is:

$$\delta ys = 10{,}000 \text{ psi}$$

$$E = 350{,}000 \text{ psi}$$

where, δys = yield strength

E = Young's modulus

If the design criteria of $\delta_{allow} \leq \frac{2}{3}\,\delta ys$, that material is limited to use in spheres for depths of less than 15,000 feet.

Several spheres were designed using that material, and they show some promise for shallow water boats. Equation D-3 was solved for the thickness of the sphere, h, giving:

$$h = \sqrt{R_i^{\ 2}\left(1 + \frac{p}{\delta - p}\right)} - R_i \qquad \text{(eq. D-4)}$$

where, h - sphere wall thickness

R_i - inside radius

p - operating pressure

δ - allowable stress

Table D-1 shows the weights and displacements of several foam spheres designed by these methods.

operating depth (feet)	operating pressure (psi)	thickness h (inches)	weight W (lbs.)	displacement Δ (pounds)	Cost ($)	W/Δ
1000	445	0.28	6.2	88.6	24	.07
2500	1116	0.77	17.9	106	68	.17
5000	2234	1.67	41.75	142	160	.29
7500	3357	3.34	102	230	390	.43
10000	4484	5.97	232	426	880	.54
12500	5615	12.15	805	1280	3060	.63

Figure D-1 shows how half a foam sphere would look. The spheres could be cast in two similar molds. The equatorial surface would be made very flat and smooth with two molded channels for power leads. The hemispheres would then be joined with an epoxy cement or a yoke-type clamp arrangement with interface gaskets.

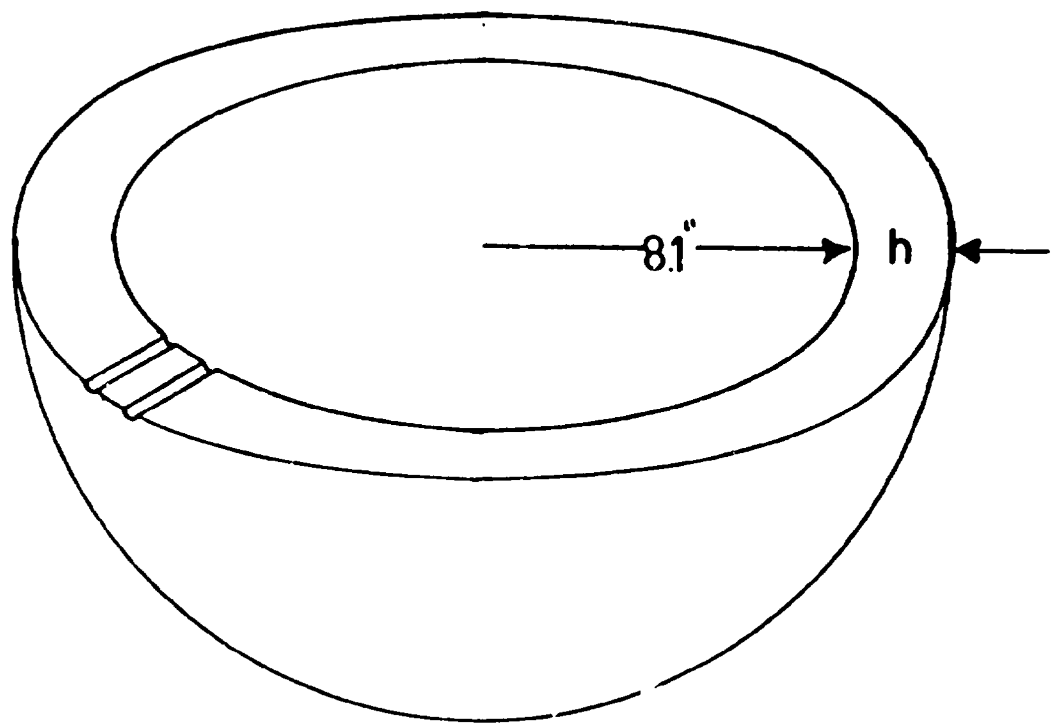


FIGURE D-1 FOAM HEMISPHERE

A P P E N D I X E

Figures E-1 through E-10 show the packing arrangement selected to accommodate the maximum number of Silvercels$^{(R)}$ in the cylinder corresponding to the height of a particular cell model.

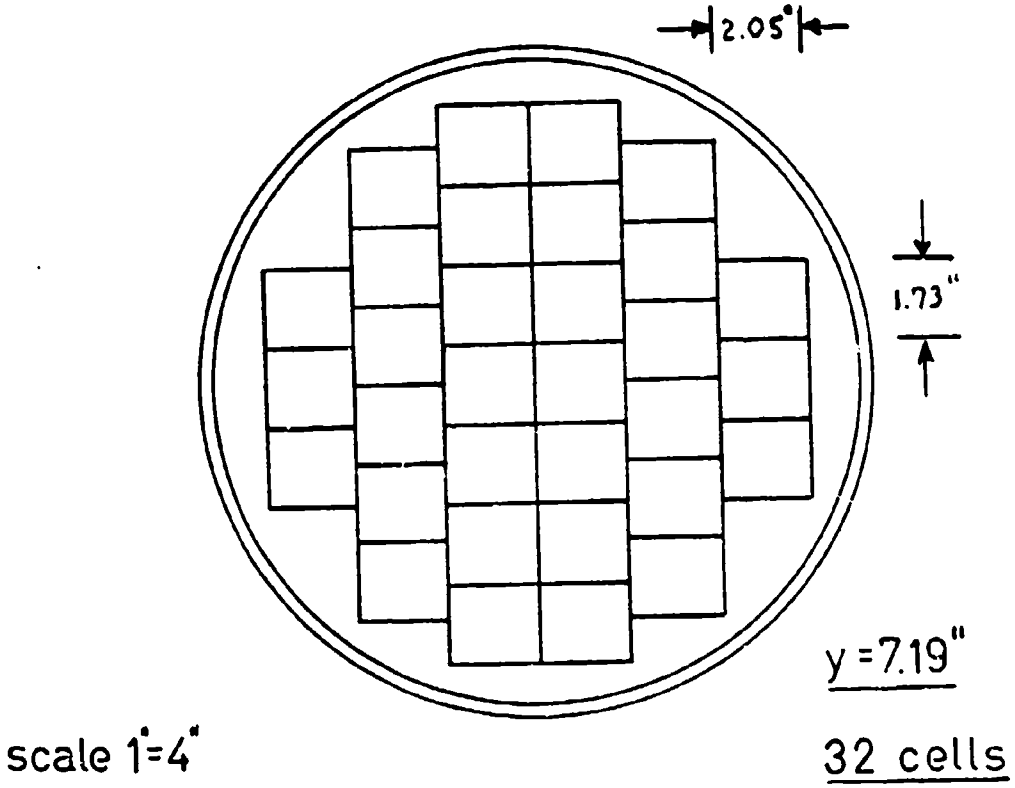


FIGURE E-1 LR-20 LAYOUT, ONE LAYER

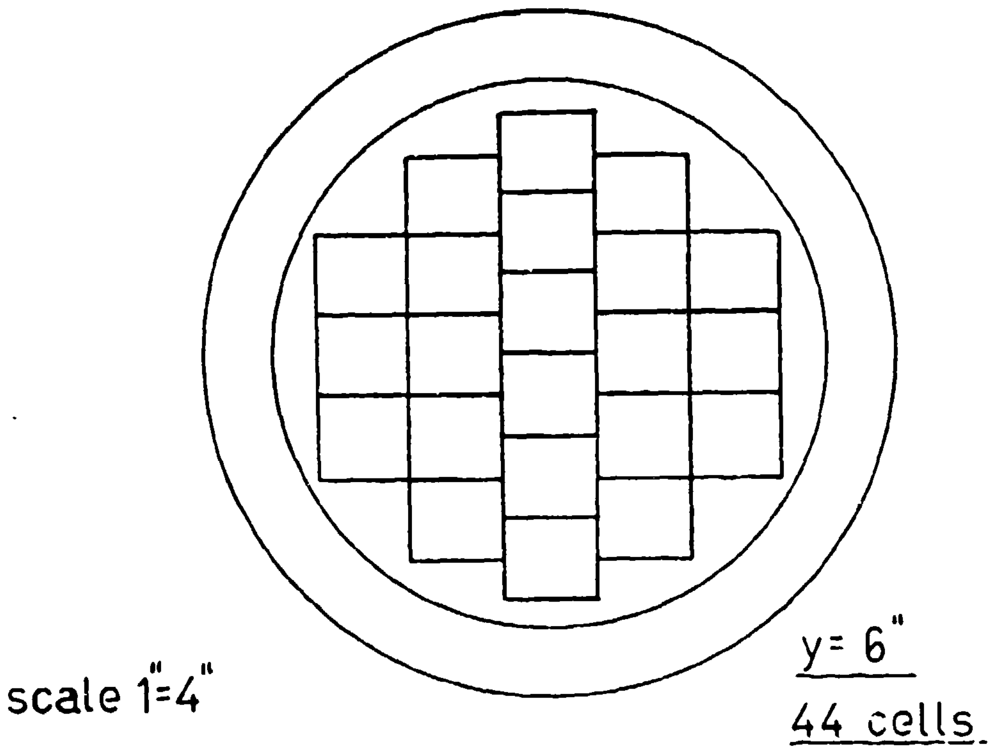


FIGURE E-2 LR-20 LAYOUT , TWO LAYERS

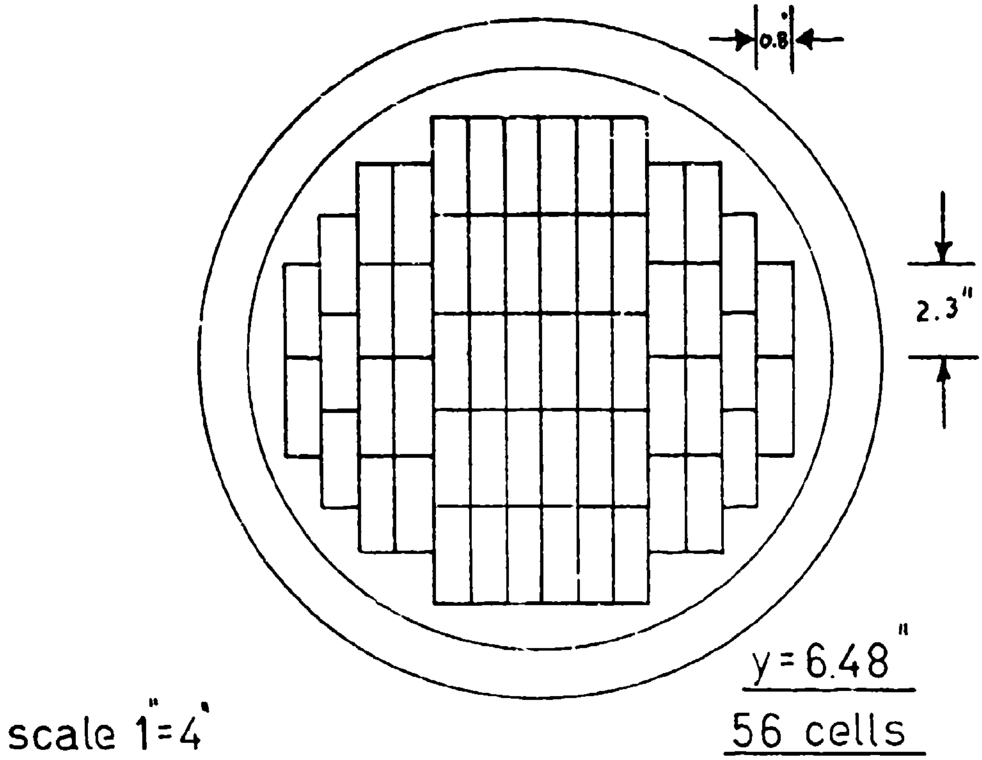
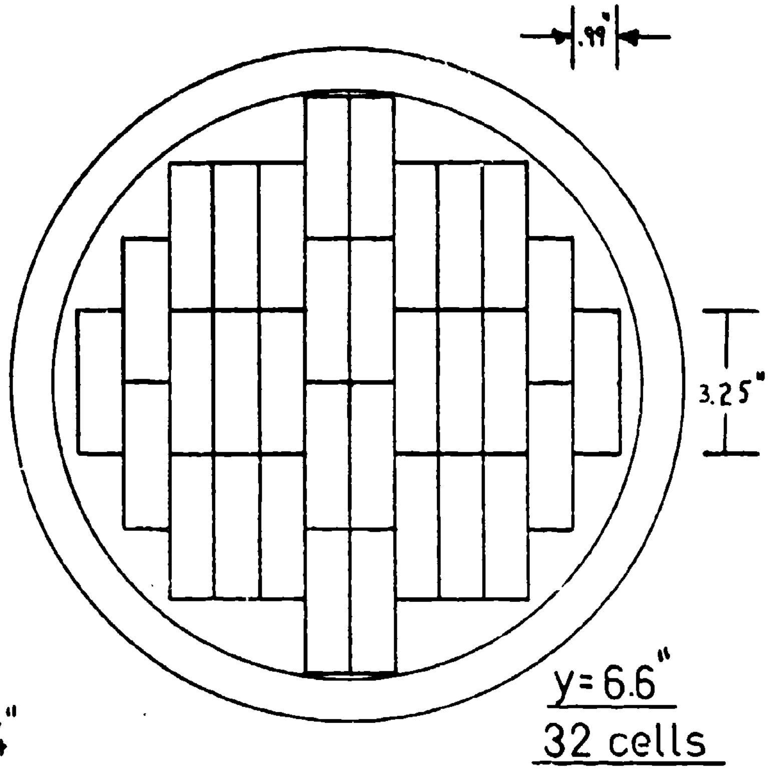


FIGURE E-3 LR-21 LAYOUT



scale 1"=4"

FIGURE E-4 LR-40 LAYOUT

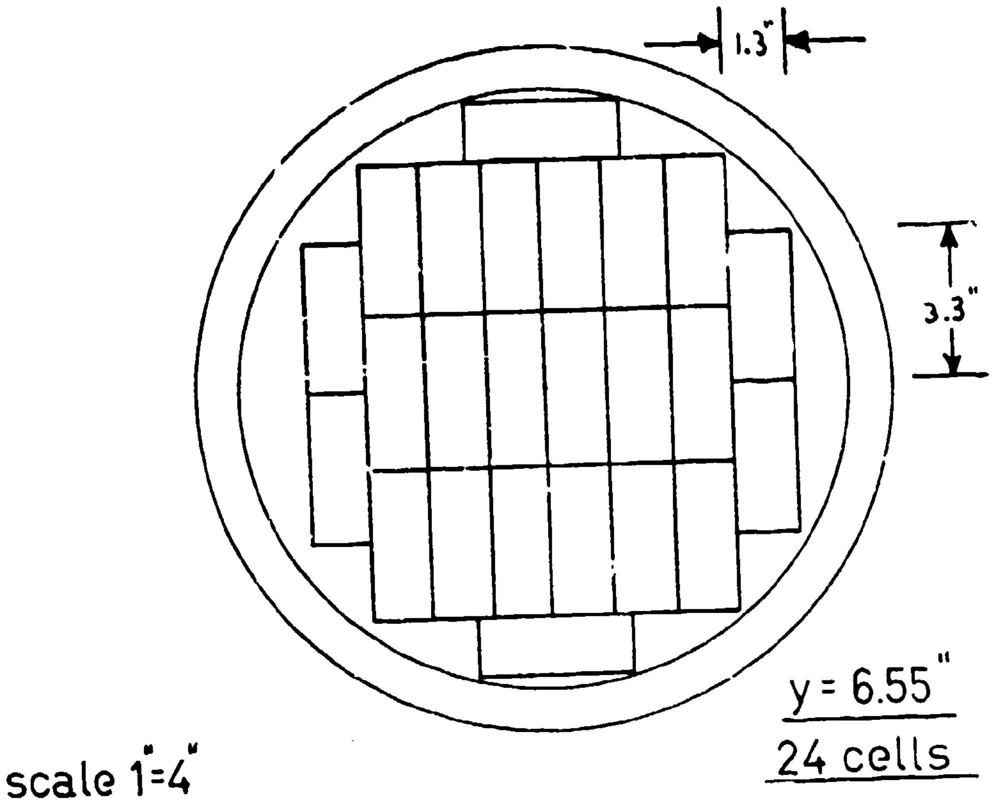


FIGURE E-5 LR-58 LAYOUT

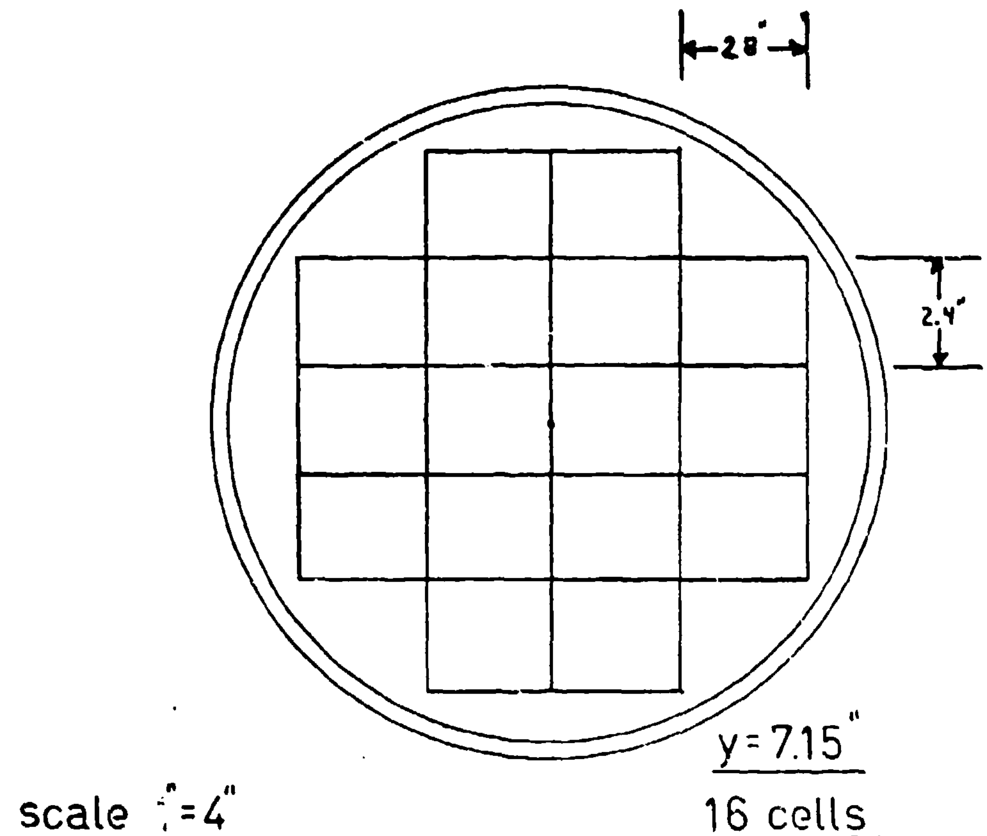
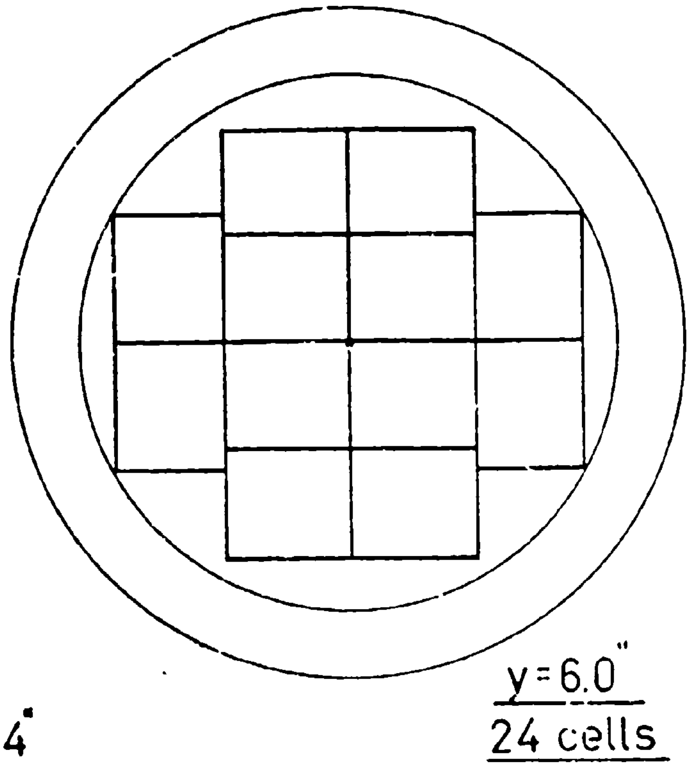


FIGURE E-6 LR-60 LAYOUT, ONE LAYER



scale 1"=4"

FIGURE E-7 LR-60 LAYOUT, TWO LAYERS

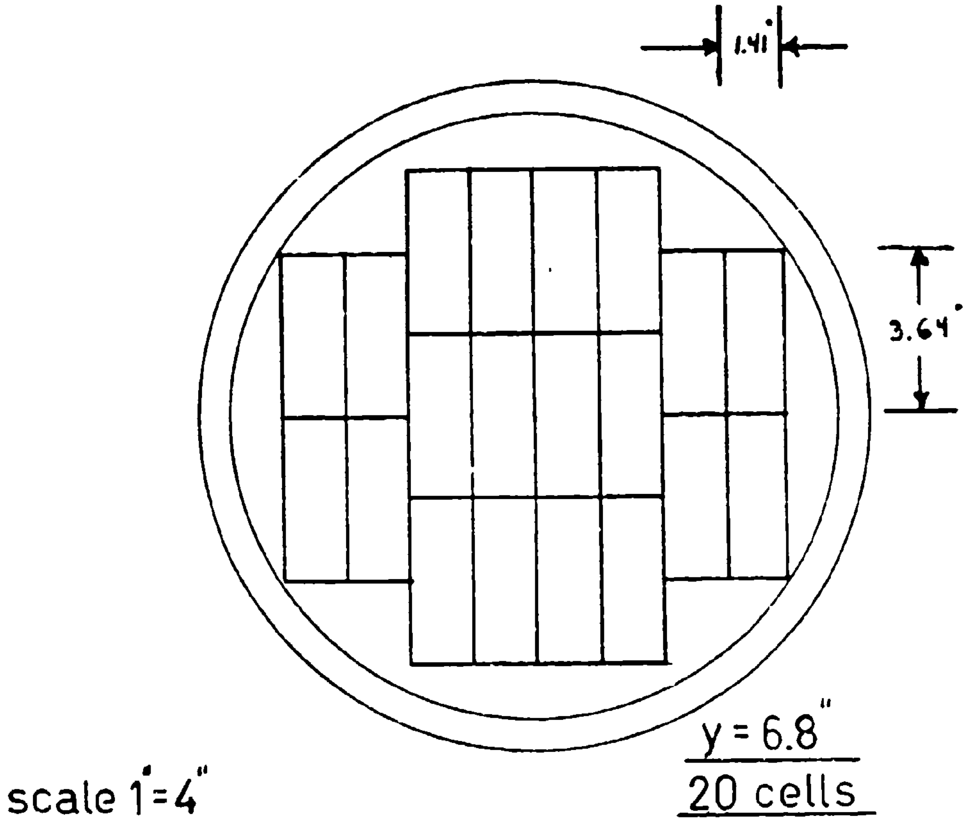


FIGURE E-8 LR-70 LAYOUT

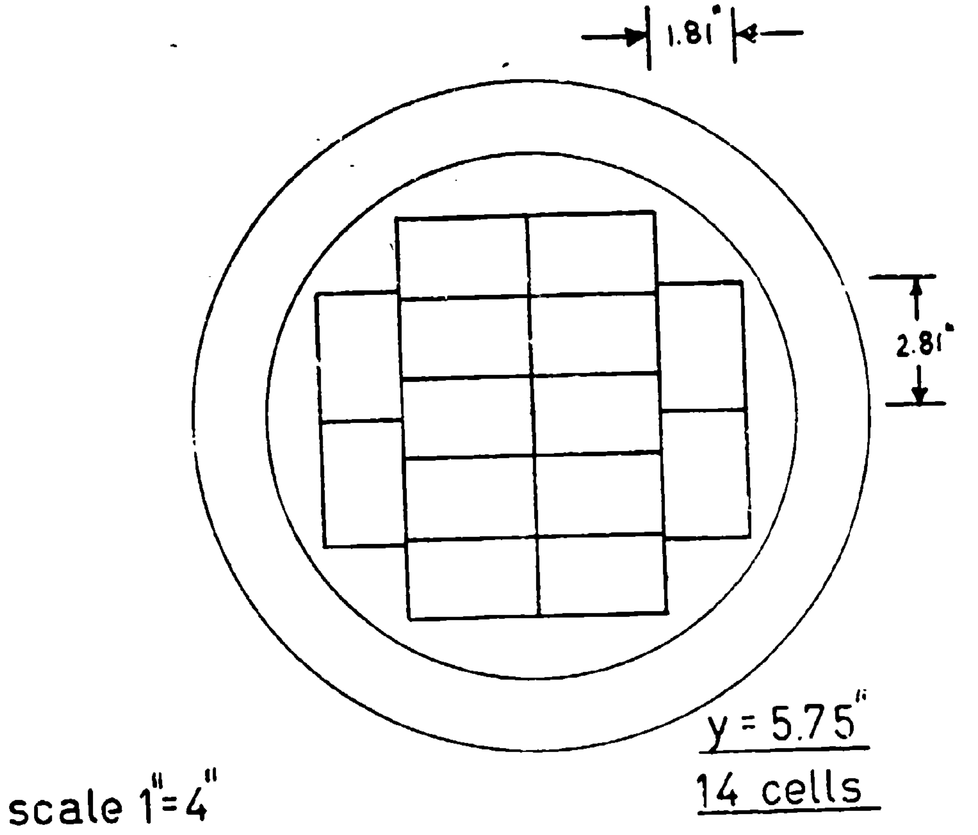


FIGURE E-9 LR-85 LAYOUT

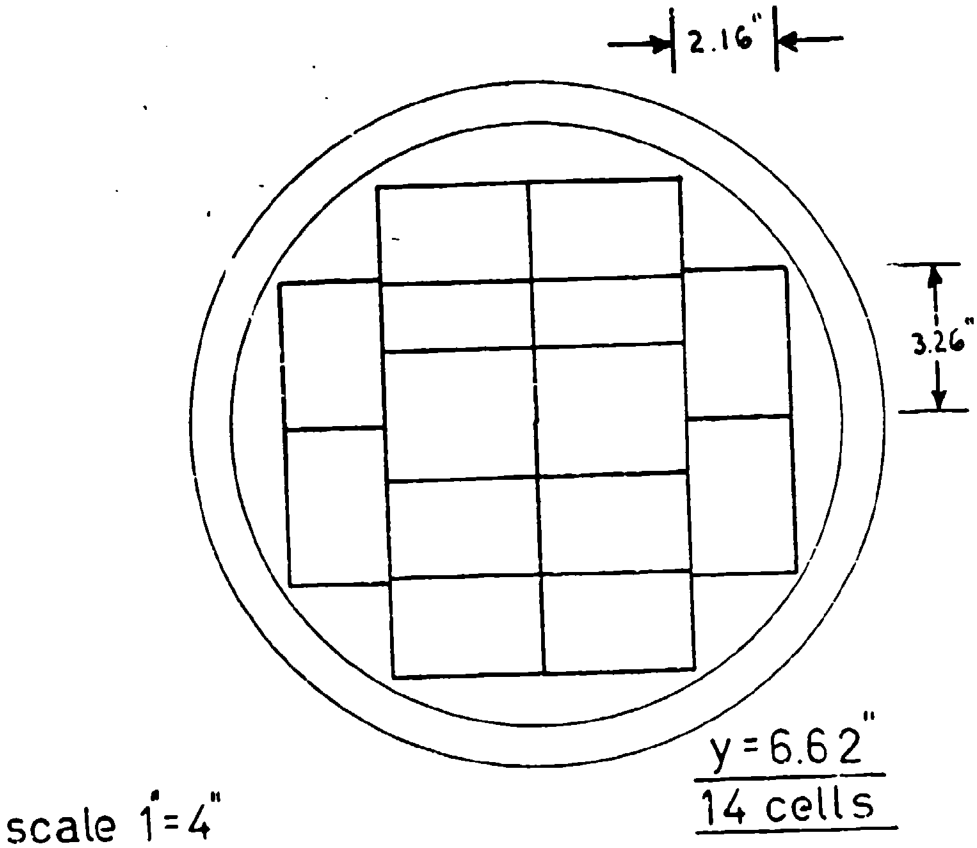


FIGURE E-10 LR-90 LAYOUT

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